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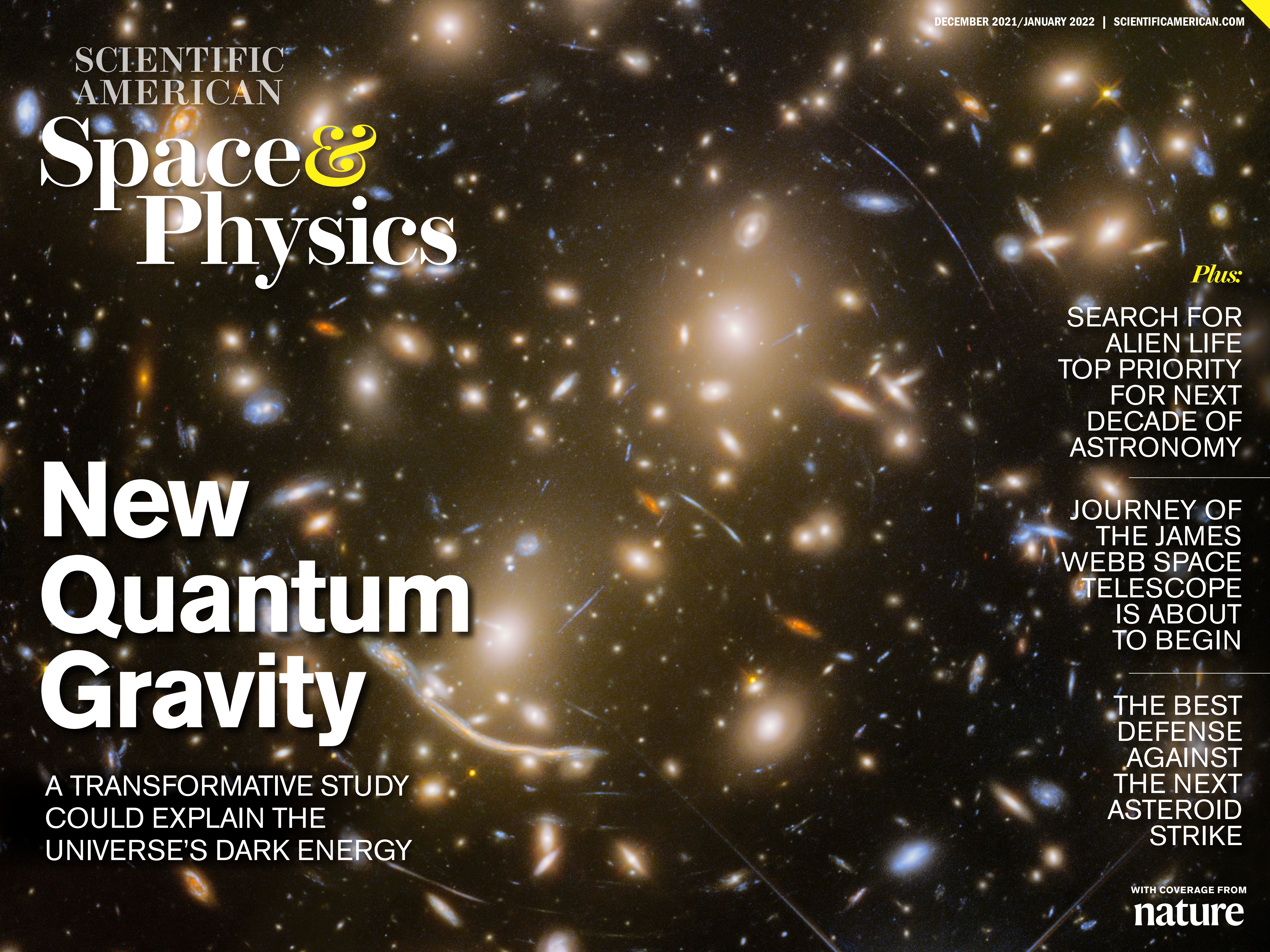

SCIENTIFIC AMERICAN

Space & Physics

Plus:

SEARCH FOR ALIEN LIFE TOP PRIORITY FOR NEXT DECADE OF ASTRONOMY

JOURNEY OF THE JAMES WEBB SPACE TELESCOPE IS ABOUT TO BEGIN

THE BEST DEFENSE AGAINST THE NEXT ASTEROID STRIKE

New Quantum Gravity

A TRANSFORMATIVE STUDY COULD EXPLAIN THE UNIVERSE'S DARK ENERGY

WITH COVERAGE FROM nature

FROM THE EDITOR

Liz Tormes

New Views across the Galaxy

At a talk in mid-November hosted by Pioneer Works in Red Hook, Brooklyn, astrophysicists Rebecca Oppenheimer and Natalie Batalha speculated on the chances that life exists on exoplanets somewhere in our galaxy. Most likely, Oppenheimer said, life is ubiquitous in the universe, but it might not take the form that we imagine. Of the thousands of exoplanets already detected, our telescopic abilities limit the level of detail we can make out, even in the nearest planetary systems. Space is just really big, and other stars and their planets are far away. As senior editor for space and physics Lee Billings writes in this issue, the near-term big goal of astronomy in this country is to devise the next-generation telescope—essentially an upgraded, supersize version of the Hubble Telescope. Likely to be completed in the 2040s, the new endeavor would scout for habitable planets in the galaxy and for alien life (see “Hunt for Alien Life Tops Next-Gen Wish List for U.S. Astronomy”).

When we look into the night sky, Batalha said, we aren’t looking at individual stars, but instead each speck of light is a planetary system and therefore a candidate for housing life. Astronomers indeed must devise grand plans to make progress while looking off-Earth. To that end, another telescope—with a price tag of $10 billion—is set to launch this December, as writer Nikk Ogasa reports (see “The Nail-Biting Journey of NASA’s James Webb Space Telescope Is about to Begin”). Yes, space is really big, but we have the ambition to see across the miles.

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Space & Physics

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NASA, ESA/Hubble, HST Frontier Fields

On the Cover

A transformative study could explain the universe’s dark energy

WHAT'S INSIDE

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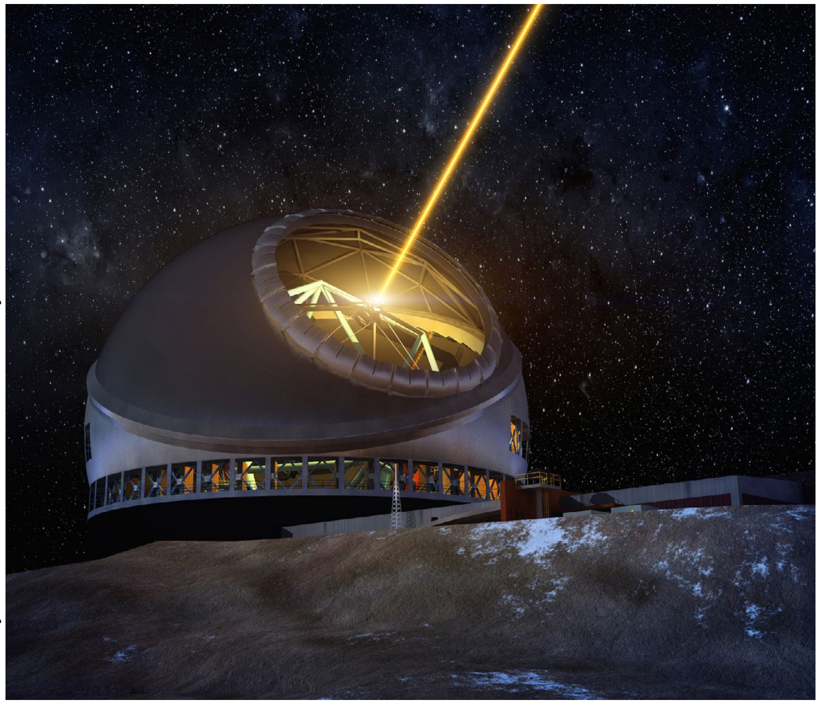
NASA, ESA/Hubble, HST Frontier Fields



Courtesy of TMT International Observatory

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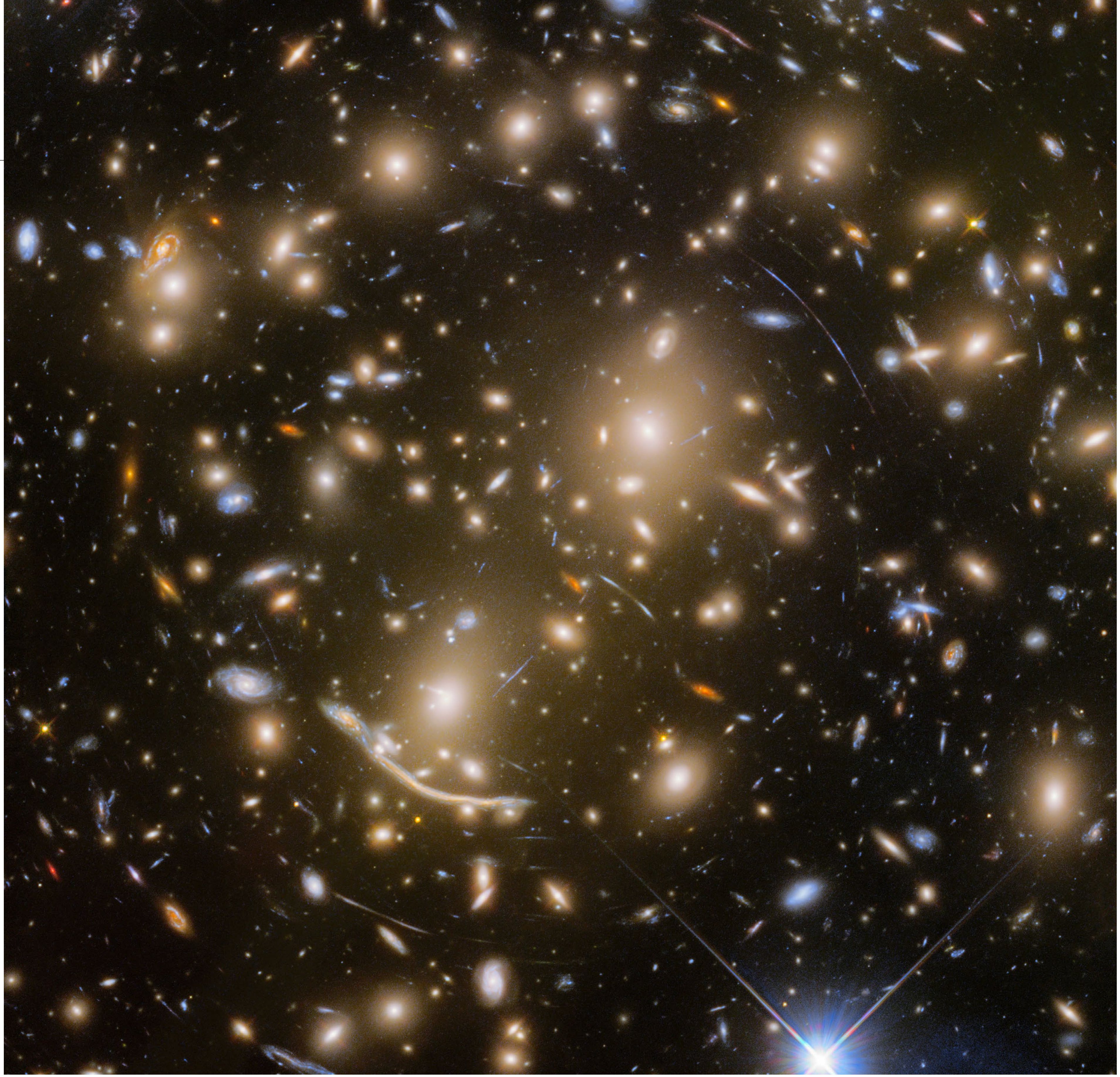
NEWS

Could Gravity's Quantum Origins Explain Dark Energy?

A potentially transformative theoretical study links a new model of quantum gravity with the universe's bizarrely accelerating rate of expansion

For decades cosmologists have wondered about the nature of dark energy, the proposed antigravitational force behind the accelerating expansion of the universe. Since the 1990s astronomers have observed that the universe is not only expanding but also increasing its expansion rate. This is very strange because the collective gravitational pull of all the "stuff" in the universe would be expected to eventually reverse cosmic expansion or at least slow it down. Instead, just like a ball gently tossed overhead suddenly soaring off into the heavens, some mysterious



Massive galaxy clusters such as this one, Abell 370, can act as gravitational lenses to amplify images of background galaxies, seen here as distorted streaks. A new theoretical study suggests gravity might also be fueling the mysterious "dark energy" speeding up cosmic expansion.

NASA, ESA/Hubble, HST Frontier Fields

force—the aforementioned "dark energy"—is pushing far-distant, galaxy-filled regions of space away from us at ever greater speeds. No known physics has fully explained this phenomenon; it remains a cosmic enigma, and its true, as yet unknown nature will profoundly shape the ultimate fate of our universe.

Now, however, a new theoretical study, submitted for publication to the *Journal for Cosmology and Astroparticle Physics*, suggests dark energy's apparent antigravitational properties may be the natural, inevitable consequence of how gravity works in the first place, at the universe's most fundamental quantum scales. If eventually verified by further cosmological evidence, the idea would represent a major breakthrough in the long quest to mend the schism between physicists' two most cherished theories: quantum mechanics, which describes the microscopic world of particles and fields, and general relativity, which describes the macroscopic cosmos of planets, stars and galaxies. General relativity posits that gravity is an emergent property of curves and warps in spacetime—the fabric of reality itself—but the theory loses its predictive power at quantum scales; conversely, quantum mechanics accurately incorporates all other known fundamental forces save for gravity, which fails to fit into the theory. Thus, many physicists suspect a quantum theory of gravity is the only way to unify these two opposing approaches.

According to Daniele Oriti, a co-author of the new paper, the core idea behind any theory of quantum gravity is that gravitation arises from a myriad of tiny, discrete, quantum objects that form a sort of hidden underworld, a deeper substructure beneath the familiar dimensions of space and time. "These quantum objects, which are very difficult to imagine," Oriti says, "are essentially the building blocks of space itself. They do not exist in space but are themselves the very stuff out of which space is made. If they exist at all, they are absolutely tiny in their size and are at a microscopic scale which even the most powerful microscopes cannot see."

In the study, Oriti and his co-author Xiankai Pang, both at the University of Munich in Germany, focused first on developing a new quantum gravity model by trying to better understand the force's properties at the microscopic level. "Once having constructed our new model," Oriti says, "we decided to track it through time from the beginning of our modeled universe, to see what would happen during the evolution of its expansion. We were definitely surprised when we saw something closely resembling dark energy. The model produced an acceleration of the expansion of the universe at the stage corresponding to the time we are at today, which matches very closely with current observational evidence."

"This is quite an elegant result," says Abhay Ashtekar, an eminent theorist at Penn State who works on modern theories of quantum gravity and who was not involved in the new study. "Because the new approach begins with a general framework for quantum gravity at the subspace level and then applies it to the cosmological scale, while in other methods one restricts oneself to the cosmological context right from start, the new idea is beginning from a more fundamental perspective than we have done before, and that is an advantage."

Oriti explains that the model's acceleration of the expansion of the universe, during the stage corresponding to today, is caused by interactions between the subspace quantum objects that make up gravity in the theory. After the expanding universe reaches a critical volume, these quantum objects begin to interact with one another in new ways. It is a bit like baking a cake. Imagine a cake where the yeast—in this case the subspace quantum objects—is not so important until a critical temperature—in this case the volume of the universe—is reached, whereafter conditions are just right to kick it into action, causing a rapid expansion. In the quantum gravity model, this is what causes the emergence of the dark energy–like phenomenon, which is characterized by an acceleration of the growth in volume of space.

"In the model, during the early universe, when the volume is small, the quantum objects out of which space emerges interact in a manner that makes them subdominant compared to their large-scale long-term evolution," Oriti says. "But then, because the universe keeps expanding through time, at some point these interactions become relevant, and they start affecting the

evolution of the universe—the dynamics of the universe—in a considerable manner, causing an acceleration of the expansion. So at that stage, the interactions between the quantum objects that make up space produce an acceleration that is similar in description and magnitude to the dark energy cosmologists observe."

"Having a dark energy phenomenological effect like this from a quantum gravity model is very interesting," says Ana Alonso Serrano, a physicist at the Max Planck Institute for Gravitational Physics in Potsdam, Germany, who was also not involved in the study. "It is important that we explore our quantum gravity models in this kind of way to see if they can make predictions about cosmology and compare them to observations."

"The next step will be to build on their theory, and their model, so to make further predictions that can be compared against real cosmological observations," she says. "But there is still a long road ahead before we really establish a good understanding about the quantum nature of gravity and indeed if there is a firm relationship with dark energy."

—Conor Purcell

New Universal Force Tested by Blasting Neutrons through Crystal

A recent experiment has placed the best yet limits on the strength of a long-sought fifth fundamental force

Experiment that blasts neutrons into silicon atoms much like waves crashing into a beach is helping physicists hunt a new fundamental force of nature.

Dan Skinner/EyeEm/Getty Images

Mysterious forces may be a reliable trope in science fiction, but in reality, physicists have long agreed that all interactions between objects evidently arise from just four fundamental forces. Yet that has not stopped them from ardently searching for an additional, as yet unknown fifth fundamental force. The discovery of such a force could potentially resolve some of the biggest open questions in physics today, from the nature of dark energy to the seemingly irreconcilable differences between quantum mechanics and general relativity. Now a recent experiment carried out at the National Institute of Standards and Technology (NIST) is offering fresh hints about a fifth force's possible character. An international collaboration of researchers used neutrons and a silicon crystal to set new limits on the strength of a potential fifth fundamental force at atomic scales. Published in *Science* last September, the study also includes measurements of the precise structure of both silicon crystals and neutrons themselves.

"This work of 'fifth force' searches actually goes on over the entire length scale of human observation," says NIST physicist Benjamin Heacock, the study's lead author. Because different theories predict different fifth force properties, he

says, physicists have looked for its subtle effects in everything from surveys of astronomical objects like galaxies to the minuscule motions of custom-built microscopic instruments. So far, however, all searches have come up empty.

"There's a reason to think we're missing something," notes Eric Adelberger, a physicist at the University of Washington who was not involved with the study. His own team has previously looked for some of the proposed new forces and, with great experimental certainty, found nothing at all. In work recognized in 2021 with a Breakthrough Prize, the researchers concluded that the fifth force must be much weaker than some theories predicted or that it simply does not exist.

The NIST experiment follows a similar idea but uses a novel experimental technique. "The goal from the experimentalist perspective is to make strides forward in limiting [the strength of] new forces, wherever the experiment can do it, and for us that happens to be on the atomic scale," Heacock says.

Gauging relevant interactions at such scales is uniquely challenging, according to Adelberger, in part because in the atomic realm a typical object is about a million times smaller than the width of an average human hair. "You have to ask, How much matter can you get within a little volume associated with that length scale? It's absolutely tiny," he says. And even the barest influence from other, known forces such as electromagnetism can easily scuttle the delicate measurements. To solve that problem, the NIST team relied on neutrons, the neutrally charged subatomic particles usually found in atomic nuclei, as neutrons are barely swayed by electromagnetic effects.

Further, the even smaller particles that make up neutrons, called quarks, are "glued" together so intensely by the strong interaction (one of the four known fundamental forces) that it is exceedingly difficult to physically disturb them. "The strong interaction that holds quarks together in a neutron is insanely strong, so the neutron gets almost no distortion when it gets close to [other] matter," explains W. Michael Snow, a physicist at Indiana University who was also not involved with the new experiment. Studying the behavior of neutrons is consequently well suited for seeking out new

"You have to ask, How much matter can you get within a little volume associated with that length scale? It's absolutely tiny."
—Eric Adelberger

forces because there are not many easily measurable effects influencing these subatomic particles to begin with. One of the new study's co-authors, Albert Young, a physicist at North Carolina State University, puts it simply: "At present, at our [atomic] length scale, neutrons kind of rule."

In their experiment, researchers observed neutrons that had traveled through a specially machined, nearly perfect silicon crystal made by collaborators at the RIKEN Center for Advanced Photonics in Japan. "Silicon is a common material, but precision machining of silicon is a super difficult thing," underlines Michael Huber, a NIST physicist and another of the study's co-authors. Inside this perfect crystal—shielded from light, heat, vibrations and other sources of external noise thanks to special NIST facilities—silicon atoms are arranged in predictable gridlike patterns.

Neutrons traveling through that grid collided with some silicon atoms and evaded others. But as the neutrons' journey took place at the atomic scale where laws of quantum mechanics dictate that all particles behave like waves, their collisions with silicon atoms were similar to breakers crashing into a shore dotted with large, evenly spaced rocks. When a neutron bumped into a silicon atom then, this interaction created something like a neutron wave ripple. This ripple overlapped with other neutron wave ripples originating near adjacent silicon atoms, resulting in a wave interference pattern not unlike rough, choppy water along a rocky coast.

Most crucially, through clever experimental design, the researchers ensured that some of the neutron "waves" lapping on the silicon atom "shores" overlapped in a very specific way that resulted in so-called Pendellösung oscillations.

These oscillations are roughly analogous to beats and are best thought of as pulsing, alternating low-then-loud auditory effects that happen when two nearly identical sound waves are played simultaneously. In the case of this new experiment, they are akin to a distinctive but difficult to detect ripple pattern within the neutron waves breaking along the silicon seashore. “Although Pendellösung interference was discovered and demonstrated a long time ago, in the 1960s at M.I.T., it's rarely used, and most experiments are not sensitive to it,” Huber explains.

His team carefully analyzed these special ripples, looking for key details about the silicon “rocks” and the neutron waves that crashed into them. It was as if they could tell how much “water” each “wave” carried, whether any “rocks” moved in the collision. More important, had an atomic-scale fifth-force interaction been at play, the details of the neutron-wave interference pattern would have revealed its presence, much like how ripples in surf can follow the outline of a submerged seawall. Although the researchers found no signs of a fifth force, they did determine a new limit, 10 times stricter than before, on how strong such a force could be.

The NIST team believes that its innovative experimental setup will allow them to make even more precise measurements in the future. The researchers already managed, for instance, to infer details of the arrangement of quarks inside a neutron, as well as some precise motions of silicon atoms, which could prove useful for the manufacture of fine-tuned electronics.

But their quest to constrain the strength of the fifth force, a task they accomplish by combining multiple separate neutron-property measurements under certain assumptions, remains the most promising and the most difficult part of their work. “We can keep and should keep searching [for the fifth force],” says Yoshio Kamiya, a physicist at Tokyo University who was not involved with the new study. “This is just one step.”

Adelberger agrees, and he is eager see new results from the next phase of experimentation. “There's a lot of stuff that has to go into getting this kind of a result,” he says. “It’s a tiny effect, and researchers have to keep accounting for all other tiny effects.”

Both Kamiya and Adelberger think that there is room for debate on how strongly the new work should make physicists reconsider their theories about the strength of a possible fifth force. Based on the current study, Adelberger says, too many potential sources of error remain; even if the NIST team had found positive evidence of a new force, he says, it could not be considered truly definitive.

Heacock notes that his team already has ideas for advancing its work, for instance by using germanium crystals instead of silicon, in which atoms are arranged in different structures that could be even more advantageous for precise observations of neutron interference. Another goal is to seriously expand the available catalog of precise atomic-scale measurements for any and all fifth-force-hunting physicists to consult in their own independent work. Ideally, Heacock notes, the measurements in the new study are just a first few opening the door for the dozens more to come. “I think any experiment will eventually hit a wall, but I also think we're pretty far from it,” he says.

—*Karmela Padavic-Callaghan*

SpaceX’s Starship Could Rocket-Boost Research in Space

The platform could aid climate science, space-junk cleanup and planetary exploration

Last September, Elon Musk’s commercial space company SpaceX launched four astronauts into orbit as part of Inspiration4, the first all-civilian spaceflight mission. They returned to Earth having made history. Yet apart from collecting data to add to a robust body of research on human health and performance in space, Inspiration4’s value as a research mission is questionable.

While eyes were on the crew and mission, the game changer to watch may instead be an ongoing SpaceX project in the background: Starship, which the company envisions will be a fully reusable transportation system. Last May, Starship SN15 became the first prototype of this system to launch 10,000 meters without anything going disastrously wrong. Starship’s inaugural successful orbital

flight could come by the end of 2022 and a flyby of the moon using the system is scheduled for 2023.

If all goes according to plan, the Starship system would lower launch costs exponentially and usher in a new era of commercial space. Indeed, as the authors of a 2021 white paper for the Planetary Science and Astrobiology Decadal Survey write, "The SpaceX Starship system fundamentally changes the paradigm for NASA science, technology development and testing, and human exploration of space."

Starship's promise has everything to do with its size and potential for reuse. SpaceX says the 120-meter-tall spacecraft will be able to transport a payload of 100 metric tons, with the greatest volume of any existing launcher. And unlike any other orbital launch system, Starship would be fully reusable, and Musk has said that this could lower launch costs to about $2 million a pop.

Launching a large telescope into space can cost more than $100 million, and reducing that price by two orders of magnitude would have an immense impact on remote sensing, says Waleed Abdalati, director of the Cooperative Institute for Research in

SpaceX successfully launched and landed Starship SN15 at the company's Starbase spaceport in Boca Chica, Tex., on May 5, 2021.

UPI/Alamy Stock Photo

Environmental Sciences at the University of Colorado Boulder. Depositing payloads of telescopes and satellites into orbit would help climate science in two ways, he says: First, by restocking devices that typically have a three- to five-year life span, Starship could create a cheaper way to carry out sustained observations of our planet. Second, it could enable more ambitious scientific missions as part of the Earth System Explorer program, which capped each one's cost at $350 million.

"If your launch vehicle eats up $60 million of that [$350 million] or more, already you're down to a pretty significant limit of resources for your actual mission," Abdalati says. "If Starship can lower that launch cost, there's more that can be directed toward the science mission itself." Astronomers have similar hopes: at least one proposed next-generation NASA telescope has already been vetted by SpaceX for a potential future Starship launch.

Indirectly, Starship could benefit the state of suborbital and orbital science by bringing space debris

back down to Earth. Space junk presents hazards to launching vehicles and operational orbiters. And any solution to reduce crowding in the skies would be "tremendously important," according to Abdalati. Such a cleanup mission could even see Starship recovering dead satellites in SpaceX's Starlink system as they grow in number—although critics might note that, in this case, the company would be cleaning up its own orbital mess and that removing defunct Starlink satellites does not alleviate the headaches the mega constellation is causing for ground-based astronomers.

Depositing payloads and reclaiming others in orbit is an added perk to Starship's stated goal, which is ferrying cargo, and eventually crews, to the moon and Mars. According to the recent white paper, whose author list includes researchers affiliated with NASA and SpaceX, the company currently plans to launch multiple uncrewed Starship missions to Mars every two years—each time exploiting a planetary alignment particularly favorable for the voyage. Without a crew, the authors write, there is great potential to unload cargo on Mars as well as to bring back samples from the planet. And similar opportunities exist for transport to and from Earth's moon. In this regard especially, Starship's sheer size is an asset. "Because Starship can return tens of tons of payload from the surface of the moon, the return sample mass of lunar samples from a single mission would dwarf the combined total returned mass of all lunar samples from all sample return missions to date," the authors write.

"If tomorrow you open a burger joint, and you tell me, 'I'm so smart; my burger will be 10 cents instead of $1.50,' I'd want to know 'Where are you going to buy your meat? Where are you going to buy bread? How are you going to pay the people who work for you?' That is exactly what is happening with Elon Musk."

—Pierre Lionnet

But it is important to interrogate SpaceX's central claim that Starship can meaningfully lower launch costs, says Pierre Lionnet, director of research at Eurospace, the trade association of the European space industry. A space economist by profession, Lionnet says that people often give outsize attention to launch cost when launching anything into space creates a number of expenses. For instance, the Rosetta space probe and Philae lander, which achieved the first-ever soft landing on a comet in 2014, cost the European Space Agency nearly €1.4 billion (about $1.7 billion), but its launch cost comprised less than 10 percent of the total bill.

The ratio of a launch cost to the total cost of creating and deploying satellites, telescopes and other devices determines which organizations will see Starship's innovation as particularly valuable, Lionnet says. "For a business, reducing the cost of launch can change the economic equation dramatically," he adds. "For a scientific program, not so much."

And while a $2-million launch cost is eye-catching, the figure does not tell the whole story, Lionnet says. SpaceX is not a publicly traded company, so it has not disclosed the costs of everything that has gone into the Starship, from building more than a dozen prototypes from scratch to employing an army of designers and engineers. Starship will have to recoup these expenses eventually, Lionnet says. This may, in part, explain the breadth of its proposed applications: SpaceX has promoted the system as not only an interplanetary ferry, space-junk remover and economical launcher for large satellites but also a point-to-point global transportation service capable of sending payloads or people to anywhere on Earth in an hour.

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exactly what is happening with Elon Musk," Lionnet says.

Others, such as former NASA deputy administrator Lori Garver, have a more optimistic outlook on Starship. In 2010 Garver helped to engineer a federal budget deal that gave NASA funding to develop partnerships with commercial space companies. She says that the tenacity of some billionaires' starry-eyed dreams of space often outweighs their unpredictability.

"Billionaires are a little riskier than a big aerospace company, but I don't think there's any question that, over the long run, they'll all be in it," Garver says. "No one's going to give up."

She adds that it is in Musk's best interest to win government contracts and use Starship to aid with research efforts to offset the start-up costs he has incurred. Winning those contracts means providing a cheaper service than an agency such as NASA could manage in-house, so there is a fixed upper limit to what SpaceX could charge a federal client. At the same time, Garver says, as Starship launches payloads more efficiently than ever before, Congress will seek to reallocate the funds previously earmarked for NASA's launch costs. Whether that money will remain with NASA depends on the agency's success at expanding into areas of public interest, such as climate solutions or human-crewed space exploration, she adds.

"The more we can do that does connect to national interests, the more money we'll get," Garver says. "The reason we ramped up during the Apollo program wasn't because 'Oh, jeez, we want to see what the moon's made of.' No, we went to beat the Russians. So what's our quest today?"

In her opinion, Starship's stated mission could serve as that quest. Zero-G music performances aside, Musk believes in using the platform to establish a colony on Mars. If you agree with the premise's value, then everything that goes into achieving this goal might then be considered a worthy scientific exploit, Garver says. And it is not a new goal.

"When I worked at the National Space Society in the 1980s, our mission was to create a spacefaring civilization," she says. "It just doesn't take much lead to know we can't survive on this planet forever."

—Maddie Bender

FAST, the World's Largest Radio Telescope, Zooms in on a Furious Cosmic Source

China's Five-Hundred-Meter Aperture Spherical Radio Telescope has detected more than 1,600 fast radio bursts from a single enigmatic system

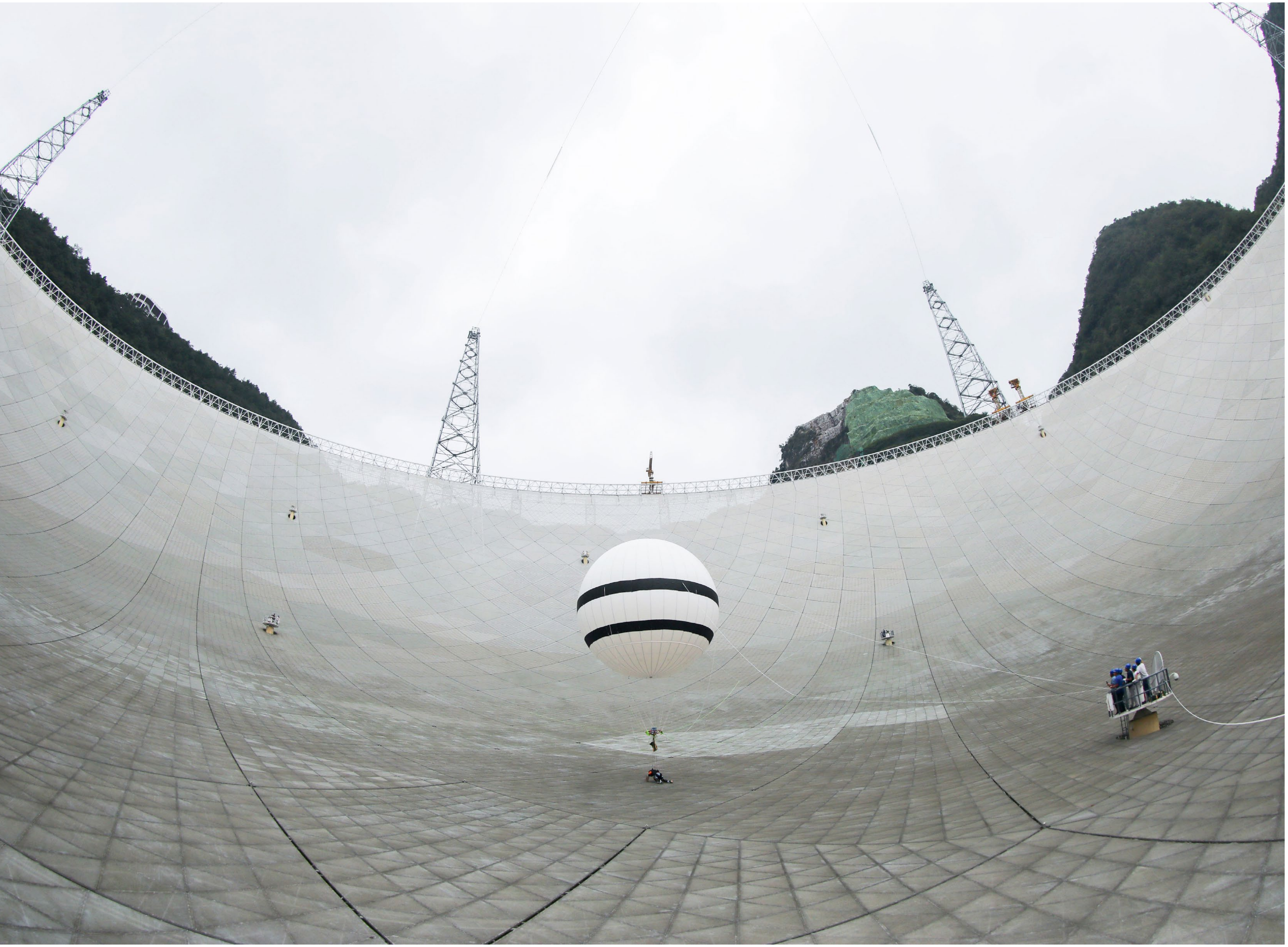
Fast radio bursts, or FRBs, are one of the greatest mysteries of our universe. Coming from deep space, these outbursts can flash and fade in a matter of milliseconds, yet in each instance can release as much energy as the sun does in a year. They pop up all across the sky multiple times a day, but most appear to be one-off events and are thus hard to catch. First discovered in 2007, FRBs have challenged and tantalized scientists seeking to uncover their obscure origins and to use them as unique tools for probing the depths of intergalactic space.

Now, using the world's largest single-dish radio telescope, an international team has reported the largest set of FRB events ever detected in history. According to their paper published in *Nature* last October, between August and October 2019 the Five-Hundred-Meter Aperture Spherical Radio Telescope (FAST) in southwestern China recorded a total of 1,652 such brief and bright outbursts from a single repeating FRB source in a dwarf galaxy three billion light-years away. Besides dramatically boosting the total number of known FRB events, the observations also revealed a very wide range of brightnesses among the recorded events, offering new clues about the astrophysical nature of their mysterious source.

"The study is very thorough, with a level of details and sensitivity we've never had before," says astrophysicist Emily Petroff of the University of Amsterdam in the Netherlands and McGill University in Canada, who is not involved in the research. "Such in-depth analyses of individual sources will be a top priority in FRB research in the near future."

A BEVY OF BURSTS

The first FRBs struck astrophysicists like thunderbolts out of a clear blue



sky; no theory had predicted their existence. Early on, researchers had little clue what the bursts could be and scrambled to come up with ideas. Explanations for FRBs have ranged from enormous magnetic eruptions on spinning neutron stars to the emissions from star-hopping alien spaceships. For a time—before FAST and other FRB-hunting telescopes began operations, anyway—the running joke among theorists was that FRB theories outnumbered the known FRB events themselves.

It was not until 2016 that observers detected the first repeating source, named FRB 121102. Statistics drawn from the ever expanding catalog of detections have now revealed

Staff member conducts maintenance of the reflector panels on the Five-Hundred-Meter Aperture Spherical Radio Telescope (FAST) with the help of a microgravity mechanism. This mechanism aims to help reduce the maintenance staff's body weight to a value within the reflector panels' range of durability using a helium-filled balloon that is 7.6 meters in diameter.

Xinhua/Alamy Stock Photo

that about 20 percent of FRBs happen more than once, and these repeating sources allow astronomers to make more detailed follow-up observations. FRB 121102 is the best studied such source so far. Prior to FAST's mother lode of new events, scientists using other radio telescopes had reported nearly 350 FRBs from this source, which is nestled in a galaxy where lots of young stars are taking shape. "With a repeating source, other telescopes usually get somewhere between two and 100 pulses. FAST did more than 1,000, which is amazing," Petroff says.

Thanks to the unprecedented sensitivity of FAST, it can catch less energetic pulses that other telescopes cannot, says Di Li, the paper's lead author and FAST's chief scientist. When the team performed test observations during the telescope's commissioning phase, it noticed that FRB 121102 was in a frenzy of activity, frequently emitting bright pulses. So the scientists decided to spare about an hour every day to monitor it. The bursts turned out to be much more intensive than expected. During some episodes, there was about one every 30 seconds.

The bursts fell into two types: ones with high brightness and others with low brightness. This may point to two distinct physical mechanisms that are responsible for the bursts, says study co-author Duncan Lorimer of West Virginia University, who co-discovered the first FRB in 2007.

It is not yet clear, however, what those mechanisms are. Even so, because the ensemble of pulses exhibited such high energies and did not show any short-term periodicity (which would suggest a source that spins or orbits at a set pace), Li believes that he and his collaborators have severely constrained the possibility that FRB 121102 comes from an isolated compact object such as a rotating neutron star or a black hole.

Others hesitate to draw the same conclusion. For instance, FRB 121102's source could still be a magnetar, a special type of neutron star with an extremely strong surface magnetic field, says theoretical physicist Zigao Dai of the University of Science and Technology of China in Hefei. Magnetars can experience "starquakes" when their outer layers adjust under stress caused by sudden shifts in stellar magnetic fields. Just like an earthquake on Earth can be triggered by different mechanisms, such as the motions of tectonic plates or the impact of an asteroid, "it remains possible for a magnetar, for instance, to go through starquakes and to frequently get hit by asteroids around it as well—a probable scenario in the galaxy [FRB 121102] lives in," Dai explains.

FRBS ON THE FAST TRACK

"FAST is really great at studies like this one—in-depth analyses of repeating sources," Lorimer says. While it is not especially adept at finding FRBs, its enormous sensitivity allows it to detect things that other telescopes miss. This is why for FRB studies FAST works best in tandem with other radio telescopes, such as the Canadian Hydrogen Intensity Mapping Experiment (CHIME), which is a powerhouse for spotting FRBs anywhere in the overhead sky thanks to its vast field of view.

Earlier in 2021 FAST announced its second open call for proposals, with 15 to 20 percent of the telescope's total observing time made available to the international community. FAST was completed in 2016, superseding the iconic Arecibo Telescope in Puerto Rico as the world's largest single-dish radio telescope.

Petroff, who is a member of the CHIME/FRB collaboration, says her team has now applied for and been rewarded observing time on FAST. According to Li, observations for approved international programs have already begun. Because international travel is still restricted because of COVID-19, foreign scientists are for now limited to remote operations and are required to submit a proof of identity, typically a copy of their passport information page, for access.

"We've been working with individual scientists to reduce their concerns and explore alternative ways of submitting personal information," Li notes. "The FAST staff warmly welcome them to come and visit once international travel normalizes, hopefully soon."

RADICAL FUTURES

FAST will keep monitoring FRB 121102 while looking into other repeating sources, Li says. In fact, he teases, his team has been working on another source, yet to be publicly revealed, that behaves "more radical-

ly" than FRB 121102. Studying run-of-the-mill as well as "radical" FRB systems, Dai says, is crucial to understanding what is and is not possible for FRBs—and thus what their true nature must be. Making further breakthroughs, he and other experts say, probably requires the coordinated efforts of multiple telescopes around the globe observing in many different types of celestial light—as well as in neutrinos and gravitational waves, too.

"I'd say FRB astronomy is still in an adolescent phase," Lorimer says. "We know quite a lot about FRBs, but there are still a number of 'growing pains' with many of the theories." The next step is to continue to pinpoint home galaxies for as many sources as possible, carrying out in-depth analyses of individual systems as Li and his team have done with FAST. With considerable effort and, perhaps, a bit of luck in finding more frenzied repeaters and radical one-off FRBs, scientists may soon solve the deep cosmic mystery of FRBs and open a new window on the high-energy, short-lived astrophysical phenomena that fill the universe.

—Ling Xin

Mercury Dazzles in New Close-up from the BepiColombo Mission

The European and Japanese spacecraft performed the first of six slingshot maneuvers around the planet. It will ultimately insert two probes into orbit in 2025

The European and Japanese BepiColombo mission has made its first fly-by of Mercury, passing just 199 kilometers above the planet's surface at 23:34 UTC on October 1, 2021.

It captured black-and-white pictures of Mercury's crater-filled surface from a distance of about 1,000 kilometers; BepiColombo flew around Mercury's nightside, so it was not able to take photographs at its closest approach. The shots were taken by auxiliary cameras at relatively low resolution because the mission's main cameras are tucked away during interplanetary travel.

The 4.1-ton, $1.85-billion spacecraft launched in October 2018 and will enter permanent orbit around

BepiColombo captured this view of Mercury from about 1,400 kilometers away. To the right, the Mercury Planetary Orbiter's magnetometer boom and part of the spacecraft can be seen.

ESA/BepiColombo/MTM, CC BY-SA 3.0 IGO

Mercury in 2025. It carries two probes, one built by the European Space Agency (ESA) and the other by the Japan Aerospace Exploration Agency (JAXA). The ESA probe will map Mercury's surface and gravitational field to study its inner structure. The JAXA probe will look at Mercury's magnetic field and its interaction with the solar wind. BepiColombo has already performed one fly-by at Earth and two at Venus, and this is the first of six it will make at Mercury. "The Mercury fly-by is special because Mercury is our target planet for our science investigations," says

project scientist Johannes Benkhoff, a planetary physicist at ESA in Noordwijk, the Netherlands.

Fly-bys are gravity-assist maneuvers, which enable interplanetary ships to either gain or lose momentum and modify their orbits around the sun without consuming large amounts of fuel. BepiColombo uses them to brake, so that it falls toward the inner solar system. This way, the spacecraft will ultimately synchronize its trajectory with that of the innermost planet, Mercury, so it can enter orbit. Some of the two probes' instruments, in particular the onboard magnetometers, collect data during the fly-bys, Benkhoff says. This could enable the team to start getting its first science results.

Once in orbit, a major focus for the craft will be water-ice deposits inside permanently shaded craters in Mercury's polar regions. The ice—which is surprising on a planet where daytime surface temperatures exceed 400 degrees Celsius—was discovered by NASA's MESSENGER mission, which studied Mercury between 2011 and 2015 and is so far the only mission to have orbited the planet.

"I'm just so excited to see Mercury close up again, even if just briefly for this fly-by," says Nancy Chabot, a planetary scientist at the Johns Hopkins University Applied Physics Laboratory. Chabot was the leading scientist for MESSENGER. "I've really missed seeing the planet," she says.

—Davide Castelvecchi

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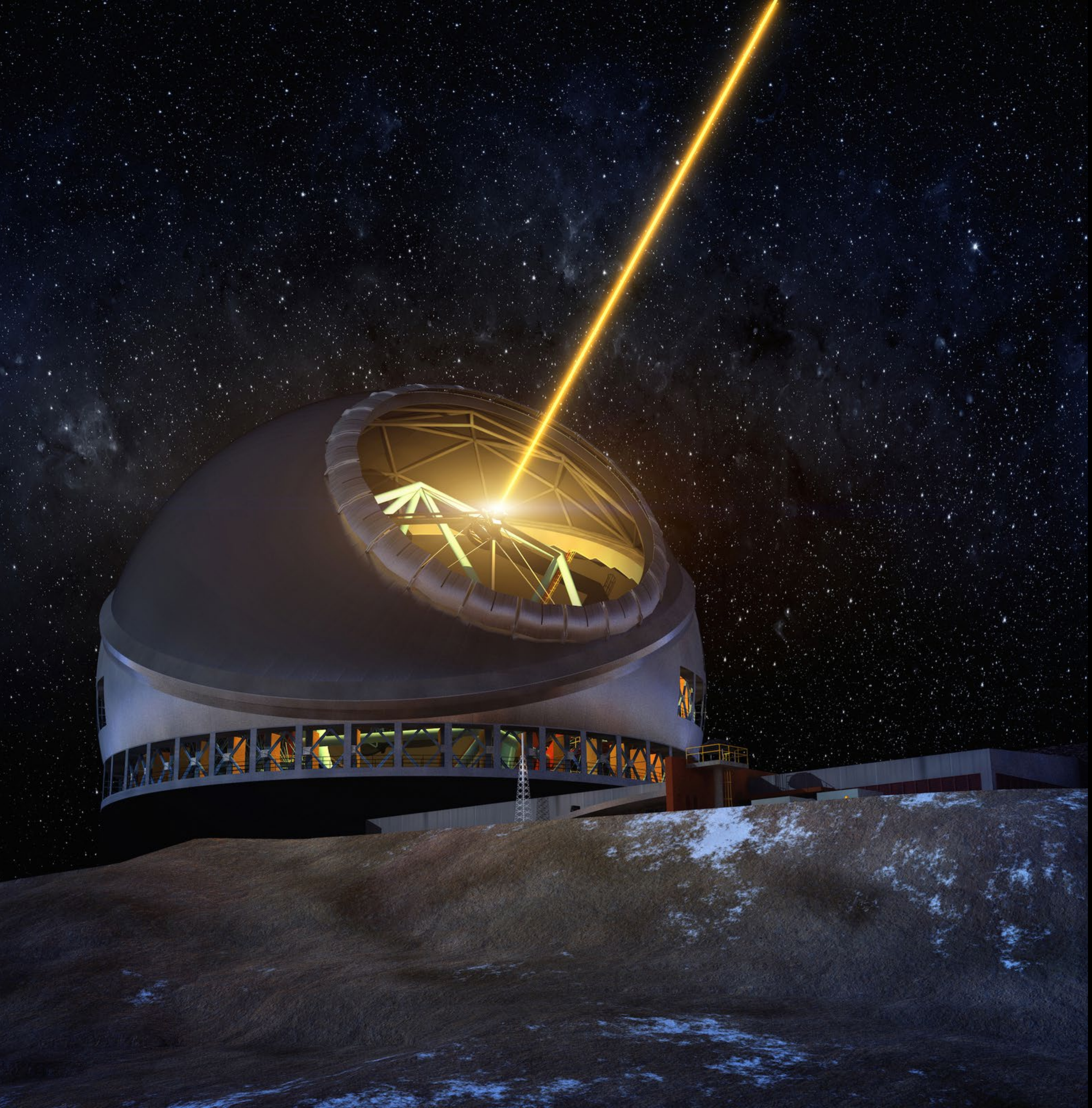

Hunt for Alien Life Tops Next-Gen Wish List for U.S. Astronomy

A major report outlining the highest priorities and recommendations for U.S. astronomy has finally been released, revealing the shape of things to come

By Lee Billings

Illustration of the Thirty Meter Telescope, an enormous (and enormously controversial) observatory that astronomers hope to build on the summit of Mauna Kea in Hawaii.

Courtesy of TMT International Observatory

Lee Billings is a senior editor for space and physics at *Scientific American*.

About 20 years from now, astronomers will be in the midst of a revolutionary era of discovery, using new telescopes on the ground and in space to study the cradle-to-grave evolution of galaxies, probe the deepest origins of black holes, glimpse the earliest moments of cosmic time and gather breakthrough images of Earth-like worlds orbiting other stars. And on average, those future researchers should also be healthier and happier, more diverse and inclusive, than their present-day counterparts.

At least that is the plan, according to the long-awaited major report "Pathways to Discovery in Astronomy and Astrophysics for the 2020s." Also known as Astro2020, the report is the seventh iteration of a once-every-10-years "Decadal Survey" process for astronomy conducted by the National Academies of Sciences, Engineering, and Medicine. Its overarching purpose is twofold: to codify communal consensus on the future of the field via a ranked list of research priorities and, perhaps more important, to muster vigorous support from federal policy makers for sustaining the broader enterprise of U.S. astronomy.

In pursuit of those goals, this latest Decadal Survey deviates sharply from its predecessors, which traditionally reserved their highest recommendations for specific new telescopes that were tightly bound to a small slice of the electromagnetic spectrum. Instead Astro2020's highest space-based recommendation envisions a fundamental shift in the way that NASA plans and develops large, multibillion-dollar "flagship" astronomy projects. Dubbed the Great Observatories Mission and Technology Maturation Program, the initiative would invest $1.2 billion in the 2020s toward key enabling technologies for multiple proposed facilities in hopes of lowering the overall cost and risk associated with building and launching an entire fleet of next-generation telescopes to work together across a wide range of wavelengths, from infrared to x-rays.

The need for better management of NASA's future astrophysical megaprojects is particularly urgent, given missteps in handling those of the present and recent past. The James Webb Space Telescope—the top flagship recommendation of the first Decadal Survey of the new millennium—is only now reaching the launchpad after a series of nearly catastrophic multibillion-dollar budget overruns and agonizing schedule slips. The top recommendation from the Decadal Survey of 2010, the Nancy Grace Roman Space Telescope, has fared better but has still suffered costly setbacks that delayed its launch until circa 2027.

The premier result of Astro2020's top-recommended new program would be a supersize and far more sophisticated successor to the Hubble Space Telescope, which itself was the first in NASA's sequence of four "Great Observatories" sent aloft between 1990 and 2003. Like Hubble, it would operate in optical, infrared and ultraviolet wavelengths, but it would be perhaps three times larger than that storied observatory and built for an estimated $11 billion. Beginning development at the end of this decade for a notional launch in the mid-2040s, it would snap pictures of dozens of potentially habitable exoplanets and study their atmospheres for signs of life while also being a workhorse for a wealth of transformative astrophysics. Although it has no catchy formal name as of yet, astronomers are already referring to this project as "LuvEx," referencing two progenitor telescope concepts—LUVOIR (Large Ultraviolet Optical Infrared Surveyor) and HabEx (Habitable Exoplanet Observatory)—that fed into its creation.

In short order, LuvEx would be followed by two additional facilities, one focused on the far infrared and the other on x-rays, each built for a projected cost of $3 billion to $5 billion. These follow-on facilities also reflect two preexisting proposals: the far-infrared Origins telescope and the Lynx X-ray Observatory.

A BRIGHT FUTURE

"This report sets an ambitious, inspirational, and aspirational vision for the coming decade of astronomy and astrophysics," said Fiona Harrison, a California Institute of Technology astronomer and co-chair of the Astro2020

> **“We stand at the threshold of a new golden era of discovery. Might we actually find evidence for life on another planet? This report, true to its name, lays out robust pathways to answer this question, and we can be the generation that answers it!”**
> ***—Heidi Hammel***

steering committee, in a statement. “In changing how we plan for the most ambitious strategic space projects, we can develop a broad portfolio of missions to pursue visionary goals, such as searching for life on planets orbiting stars in our galactic neighborhood—and at the same time exploit the richness of 21st-century astrophysics through a panchromatic fleet.”

Many astronomers are understandably ecstatic. “I believe this is the smartest, most executable and pragmatic Decadal Survey ever written,” says John O’Meara, a vocal champion of the LUVOIR concept and chief scientist of the W. M. Keck Observatory on Mauna Kea in Hawaii. “The steering committee understood that we must redefine how we develop large missions so that we can realize this vision of new Great Observatories. They have brilliantly laid out how to achieve civilization-changing science in an uncertain world, and I hope NASA and other federal agencies embrace the spirit of the document.”

“We stand at the threshold of a new golden era of discovery,” says Heidi Hammel, vice president for science at the Association of Universities for Research in Astronomy. “Might we actually find evidence for life on another planet? This report, true to its name, lays out robust pathways to answer this question, and we can be the generation that answers it!”

Marc Postman, a distinguished astronomer at the Space Telescope Science Institute and a long-time proponent of large exoplanet-imaging observatories, holds a somewhat longer but no less gleeful view. “I’m walking on air right now because this is the culmination of a personal 15-year journey to get to this point. People ask me why I’ve spent time on this, because, when [LuvEx] launches, I will certainly be retired but hopefully still in my mortal shell. I tell them I’m doing this for the future even if I never use it or see it get off the ground. And based on this Astro2020 report, the future is very bright. This is a generational initiative that is beyond any individual. Humanity is about to truly embark on a quest to learn whether we are alone in the universe.”

Besides the big-ticket item of a life-hunting telescope as the first of a line of flagship Great Observatories, Astro2020’s space-based recommendations also call for new once-per-decade “probe-class” missions with $1.5-billion cost caps, as well as significant spending to enhance astronomers’ abilities to study split-second celestial phenomena in real time using not only light but subatomic particles and gravitational waves as well.

Astro2020’s purview also extends to U.S. ground-based projects, which are typically funded and managed by the National Science Foundation (NSF) or occasionally by the Department of Energy. In this category, the report gives top ranking to a program to invest some $1.6 billion of NSF funding in the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT), two gargantuan observatories in early phases of construction with an estimated total price tag in excess of $5 billion. With the GMT in the Southern Hemisphere—on a Chilean mountaintop—and the TMT in the Northern Hemisphere—either on the summit of Hawaii’s Mauna Kea or a peak on La Palma in Spain’s Canary Islands—U.S. astronomers would gain profound new views of the whole sky through these extremely powerful telescopic eyes.

Other than helping these twin titans across the finish line, the report also recommends that the NSF and DOE jointly spend $660 million to create the Cosmic Microwave Background Stage 4 Observatory (CMB-S4), a facility to survey the big bang’s afterglow in exquisite detail. An additional $2.5 billion of NSF funds would go to building the Next-Generation Very Large Array (ngVLA), a radio observatory that would be 10 times more sensitive than the aging facilities it would replace. Additionally, Astro2020 strongly endorses further upgrades to two projects opening entirely novel windows on the cosmos: the Laser Interferometer Gravitational-wave Observatory (LIGO) and to the IceCube Neutrino Observatory, a facility with thousands of detectors arranged within a cubic kilometer of Antarctic ice. Paired with traditional observatories, LIGO and IceCube can help astronomers divine the arcane mechanics at play within the cores of exploding suns and between merging black holes and neutron stars.

POWER TO THE PEOPLE

The pathway forward may be clear, but abundant obstacles remain. Much depends on whether Congress and the White House fully embrace—and fund—Astro2020’s recommendations, a prospect not at all certain in the modern era of hyperpolarized politics. Then there is the looming issue of satellite megaconstellations. Despite their benefits for global broadband connectivity, these groups of satellites pose existential threats to multiple major projects via the optical and radio con-

tamination they inescapably add to exquisitely delicate observations of the heavens. For that increasingly dire problem, Astro2020 offers only the rather dissatisfying solution of engaging in interagency, as well as international, collaboration to devise better, more protective regulatory frameworks.

But as the authors of the report themselves note, despite such challenges, the success of their audacious vision may ultimately hinge on how they handle the most valuable assets of U.S. astronomy, which are not dollars but people.

"Our report says serious attention also needs to be paid to investments in the foundations of this research—including in the people who carry it out," said Astro2020 steering committee co-chair Robert Kennicutt, an astronomer who holds professorships at the University of Arizona and at Texas A&M University, in a statement.

That recognition, deep in the Decadal Survey's bones, is one reason Astro2020 is "a huge win for U.S. astronomy," says Scott Gaudi, an astronomer at the Ohio State University and co-chair of the HabEx mission concept study. "The decadal steering committee really thought about how to create a balanced portfolio—not just with a new set of Great Observatories and projects like the GMT and TMT but also with significant support for basic things like more research grants and midscale programs. And that's exactly what we need to make the more ambitious parts of this vision even plausible in the first place."

In recent years the community has been left reeling not only from budget-blowing projects but also from sexual harassment scandals, anemic support for early-career researchers and their smaller-scale projects, and brutal asymmetries in work-life balance that have led to burnout and poor well-being. There is also a worrisome lack of diversity among the ranks. In this melting-pot nation, the typical practitioners of astrophysics remain overwhelmingly white and male, with all the privileges, obvious or subtle, this entails—something keenly felt when, for instance, some of them seek to build new facilities on the sacred grounds of historically disenfranchised minority groups, as is the case of the TMT and the project's preferred construction site on Mauna Kea.

To remedy these and other social ills, Astro2020 recommends more spending on research grants and independent postdoctoral fellowships, increased funding and institutional support for diversity-boosting initiatives at the university and federal-agency level, and a formal recognition at NASA, the NSF and the DOE that harassment and discrimination are corrosive forms of scientific misconduct. With the TMT imbroglio at Mauna Kea clearly in mind, the report also calls for a "Community Astronomy" model of engagement that would seek to "respect, empower, and benefit local communities while advancing scientific research," according to a National Academies press release.

Such acts, says University of New Hampshire cosmologist Chanda Prescod-Weinstein, would be "steps in the right direction" to address the growing storm of cultural crisis cresting over the field's horizons. But even so—especially in the case of engaging with historically marginalized Indigenous people—she says this Decadal Survey's recommendations do not go far enough.

"Sometimes scientists have to accept a hard 'no' from Indigenous people," Prescod-Weinstein says. "Instead [Astro2020] focuses more on what the characteristics and quality of a collaboration between Indigenous communities and scientists should be. It never directly acknowledges the scenario that Indigenous people may not want to collaborate.... My view may change once I've had more time to sit with the report, but my first impression is that scientific goals are still supreme and that we are still not ready, as a community, to talk to nonastronomer Indigenous people as if they are our equals and their concerns matter as much as ours." SA

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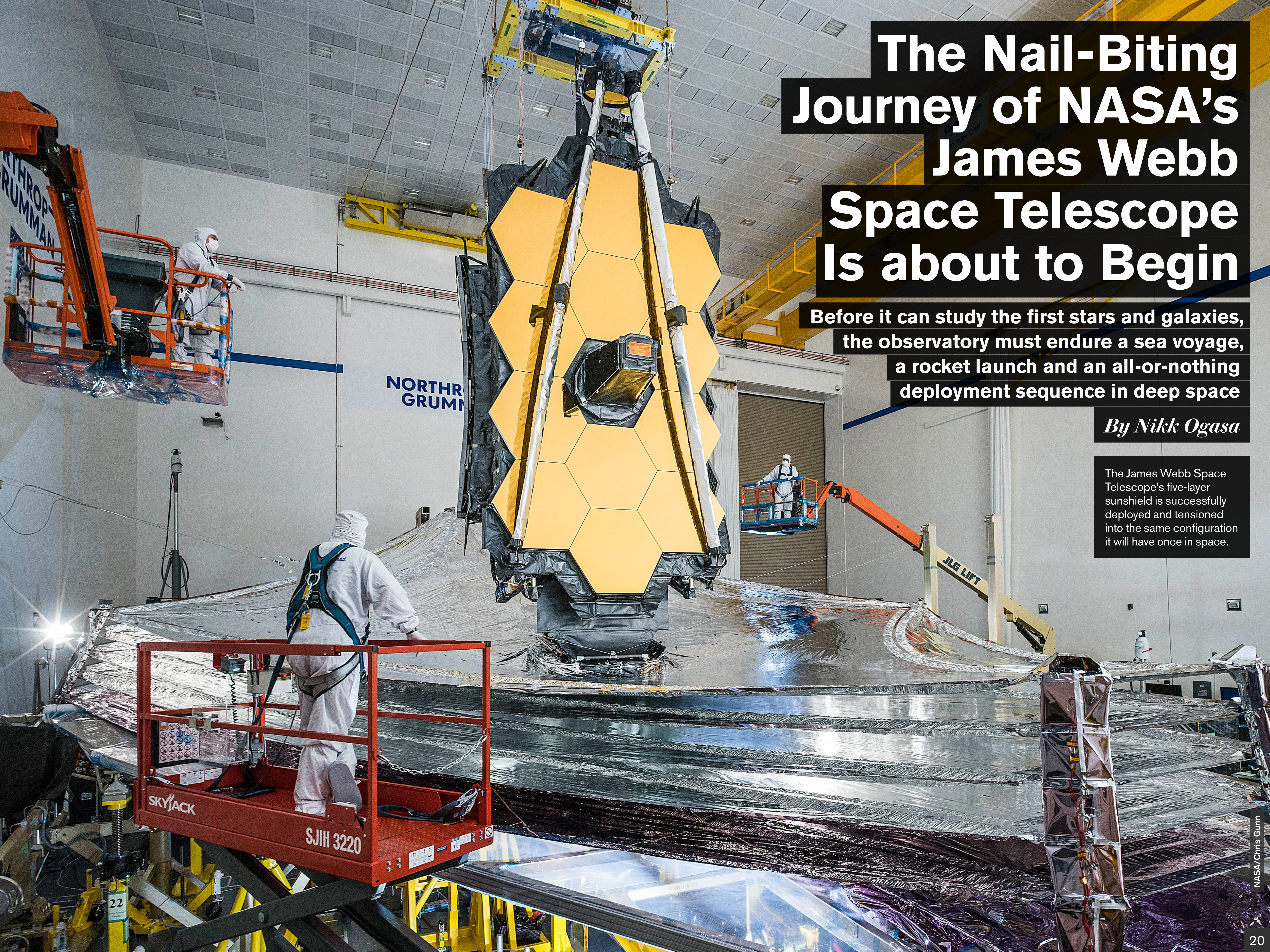
The Nail-Biting Journey of NASA's James Webb Space Telescope Is about to Begin

Before it can study the first stars and galaxies, the observatory must endure a sea voyage, a rocket launch and an all-or-nothing deployment sequence in deep space

By Nikk Ogasa



The James Webb Space Telescope's five-layer sunshield is successfully deployed and tensioned into the same configuration it will have once in space.

NASA/Chris Gunn

Nikk Ogasa is a California-based science journalist with a fondness for the environment, Earth and space. He is an editorial intern at *Scientific American.*

IN SEPTEMBER, NASA announced that on December 18, 2021, after years of delays, the James Webb Space Telescope will finally leave Earth on a mission to revolutionize astrophysics and cosmology.

But before this $10-billion observatory can begin its work, it must survive a daunting commute that includes a voyage at sea, a rocket launch and a 1.5-million-kilometer flight to its destination: Lagrange point 2, or L2. Far beyond the orbit of the moon (and out of reach of any near-term rescue mission), L2 is a region where the gravitational tugs of Earth and the sun balance out to create a perfect long-term parking place for telescopes. As Webb leaves our planet and moon behind, it must also deploy key components that were folded up to fit inside its rocket. This high-tension process involves some 178 release mechanisms, each of which must operate flawlessly for the telescope to complete its 40 or so major deployments.

"This is the most complex scientific mission that we've done," says Nancy Levenson, deputy director of the Space Telescope Science Institute (STSci). "There's a lot that has to go right."

Webb is without question the most advanced space telescope ever built. The spacecraft's infrared gaze will penetrate cosmic clouds of dust to reveal the hidden details of stellar nurseries and embryonic protoplanets midway through formation. It will also gather the faint photons effused by the first stars and galaxies to form after the big bang—which were initially emitted as visible light but have since been stretched, or "redshifted," by the expansion of the cosmos.

"It's going to help us unlock some of the mysteries of our universe," says Greg Robinson, Webb's program director at NASA. "I want to say it's going to rewrite the physics books."

But that assumes all goes according to plan.

BY LAND AND SEA

Webb's journey began in Redondo Beach, Calif., at the Northrop Grumman facility where its construction and final tests were completed. There the spacecraft, which is currently folded up, was placed into a specialized shipping container called the Super Space Telescope Transporter for Air, Road and Sea, or Super STTARS. The custom travel pod will protect Webb from humidity, vibrations and fluctuating temperatures.

Later, while housed within its high-tech cocoon, Webb was transported to the city's harbor and placed on a boat. The exact date of departure was kept under wraps to stifle piracy, says Massimo Stiavelli, head of Webb's mission office at STScI.

Details about the security accompanying the telescope have not been made public. Even so, Stiavelli says that he is unconcerned about pirates stealing the precious cargo, thanks to numerous undisclosed but very real security measures put in place for the maritime trip. In the event of a high-seas heist attempt, he says, "I would worry about [the safety of] the pirates themselves."

After departing from shore, the telescope, still contained in Super STTARS, voyaged south along the coast and through the Panama Canal. Webb entered the Caribbean in early October—that is, during hurricane season.

Safe harbors were identified all along the spacecraft's shipping route. And weather conditions were monitored closely to ensure that it would not unexpectedly find itself caught vulnerable in a storm, Stiavelli says.

After about two weeks at sea, the telescope arrived at the port and European Space Agency (ESA) launch site of Kourou, French Guiana. There Webb is undergoing launch preparations, which include fueling it, performing final electronics checks and, of course, mounting the spacecraft on its celestial steed: ESA's Ariane 5 rocket.

Still folded, the 6,500-kilogram telescope will be secured inside the top of the rocket, within a chamber called the fairing. Once positioned, Webb will be ready to take to the skies.

BLASTING OFF

Presuming no further delays in its path to the launchpad, early in the morning of December 18, Webb will blast off with a slight eastward trajectory over the Atlantic Ocean. Its Ariane 5 rocket is considered a reliable workhorse, and the telescope itself has passed tests meant to mimic the stresses of a launch, so confidence is high that the journey to orbit will go smoothly, Robinson says.

Still, "one of the largest sighs of relief will be a successful launch," says Heidi Hammel, a vice president at the Association of Universities for Research in Astronomy. "As we say in the business, this is rocket science. We're putting this incredibly precious resource on top of a rocket and setting the fuse, so to speak."

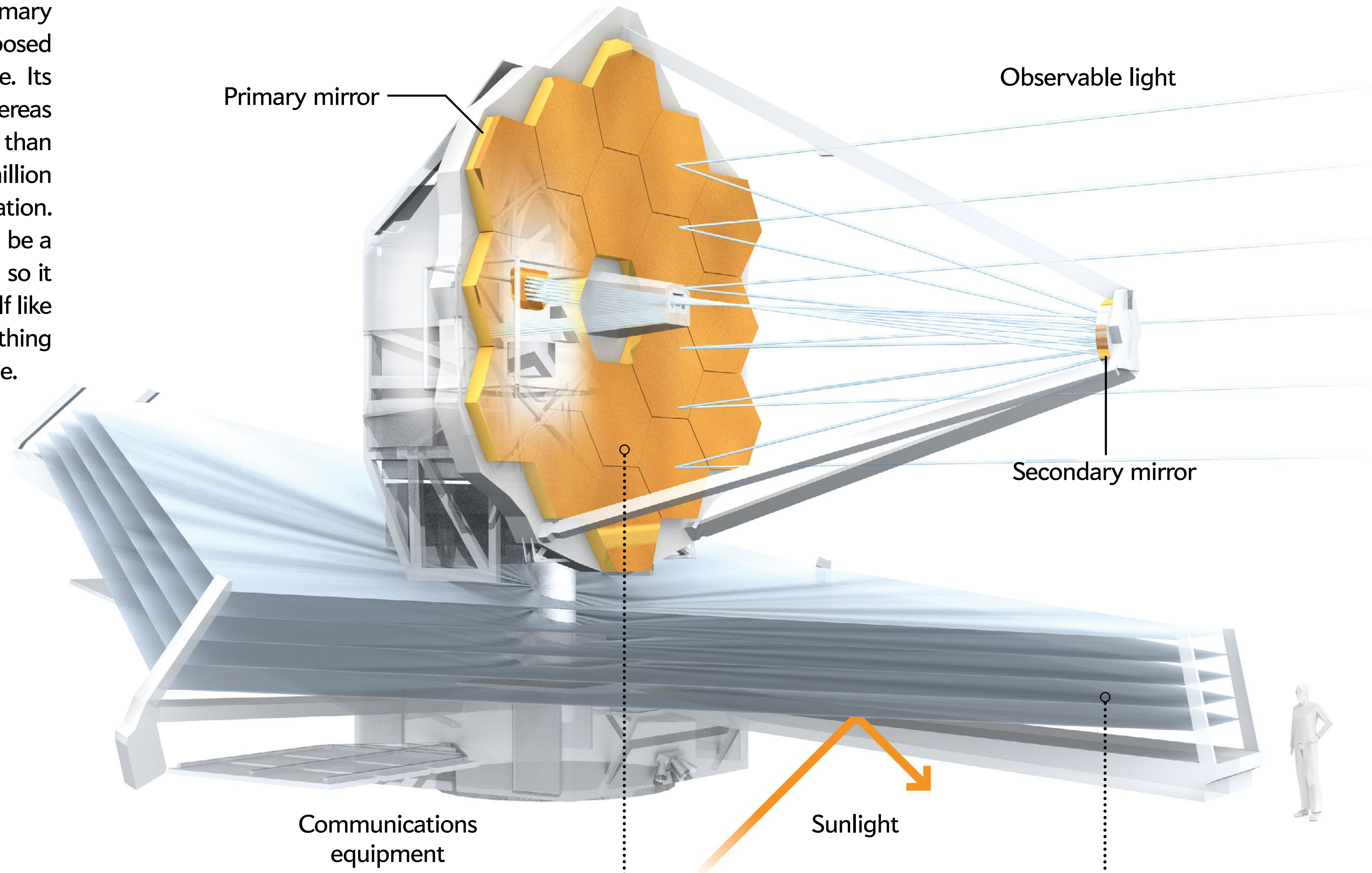
New Eyes on the Cosmos

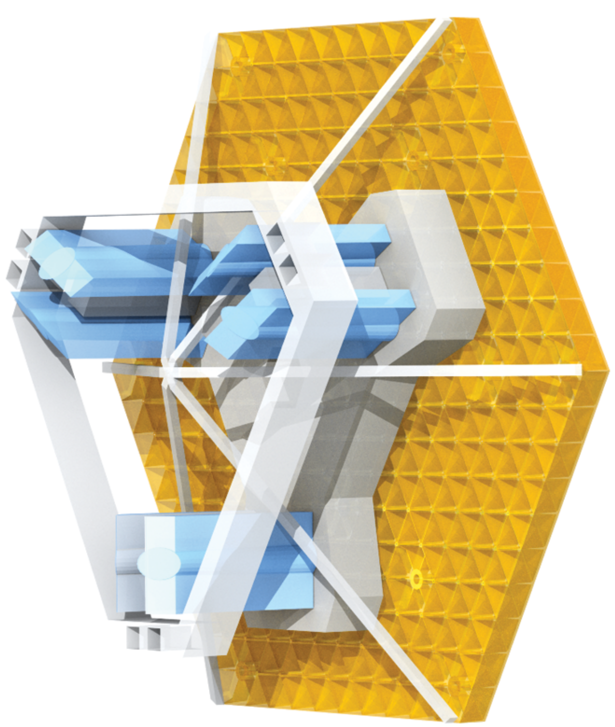
Though often described as the Hubble's successor, the James Webb Space Telescope has little in common with NASA's current astronomy workhorse. Its primary mirror has six times the surface area and is composed of 18 adjustable segments rather than one piece. Its instruments are sensitive to infrared radiation, whereas the Hubble's see mostly visible light. And rather than circling Earth itself, the Webb will hover nearly a million miles away, the better to avoid Earth's heat radiation. The telescope's dramatic deploying maneuver will be a nail-biter: the plan is to crumple the telescope up so it can fit on a rocket. Once in space, it will unfurl itself like a newborn butterfly spreading its wings. If something goes wrong, the telescope could remain inoperable.

This graphic was originally produced for the October 2010 issue of *Scientific American*.

The Instruments

The Webb will carry a mid-infrared camera, a near-infrared camera and a spectrograph. Its angular resolution will be comparable to that of the Hubble's, but because of its exquisite sensitivity in the infrared it will still see objects farther away—and thus farther back in time.





Mirror Segment

The beryllium hexagons that make up the primary mirror are polished to a tolerance of tens of nanometers and sculpted so they will assume the correct shape when plunged into the deep cold of the parasol's shadow. The segments' back sides were carefully chiseled to reduce weight. Seven motors will adjust the shape and orientation of each segment, with an accuracy of tens of nanometers, to respond to small thermal deformations that would reduce image quality.

The Parasol

The volleyball-court-size sunshield will shelter the telescope from the sun so its electronics and optics stay at temperatures below 55 kelvins and thermal noise does not interfere with infrared cameras. The bottom layer will reflect most of the sunlight, and each successive layer will reflect thermal radiation from the previous one.

Bryan Christie Design

The Vision

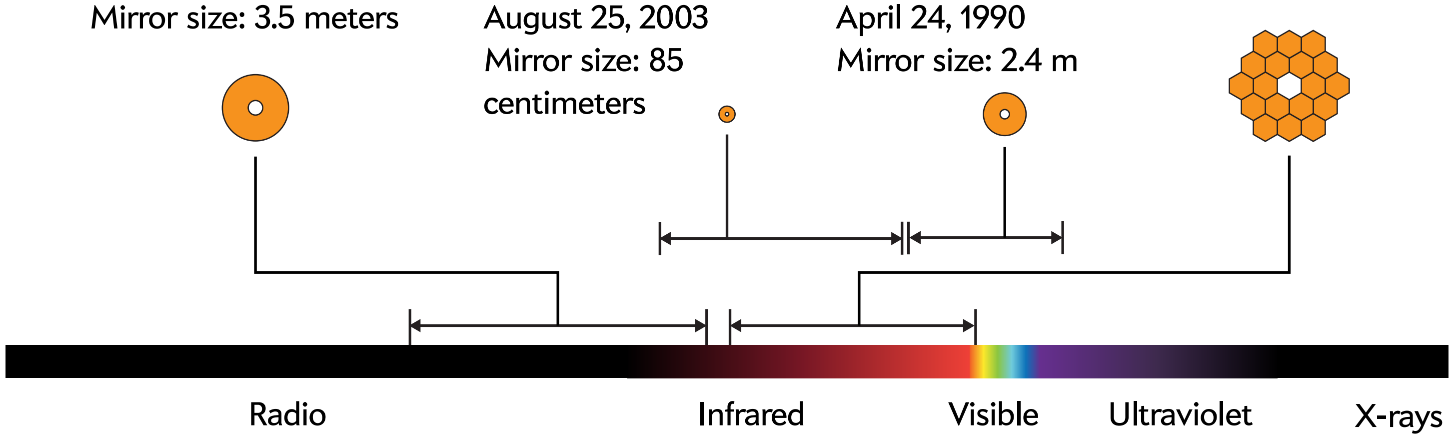
The new telescope will operate in a part of the spectrum covered by previous missions but will do so with better sensitivity and resolution.

Herschel Space Observatory
Launch: May 14, 2009
Mirror size: 3.5 meters

Spitzer Space Telescope
Launch: August 25, 2003
Mirror size: 85 centimeters

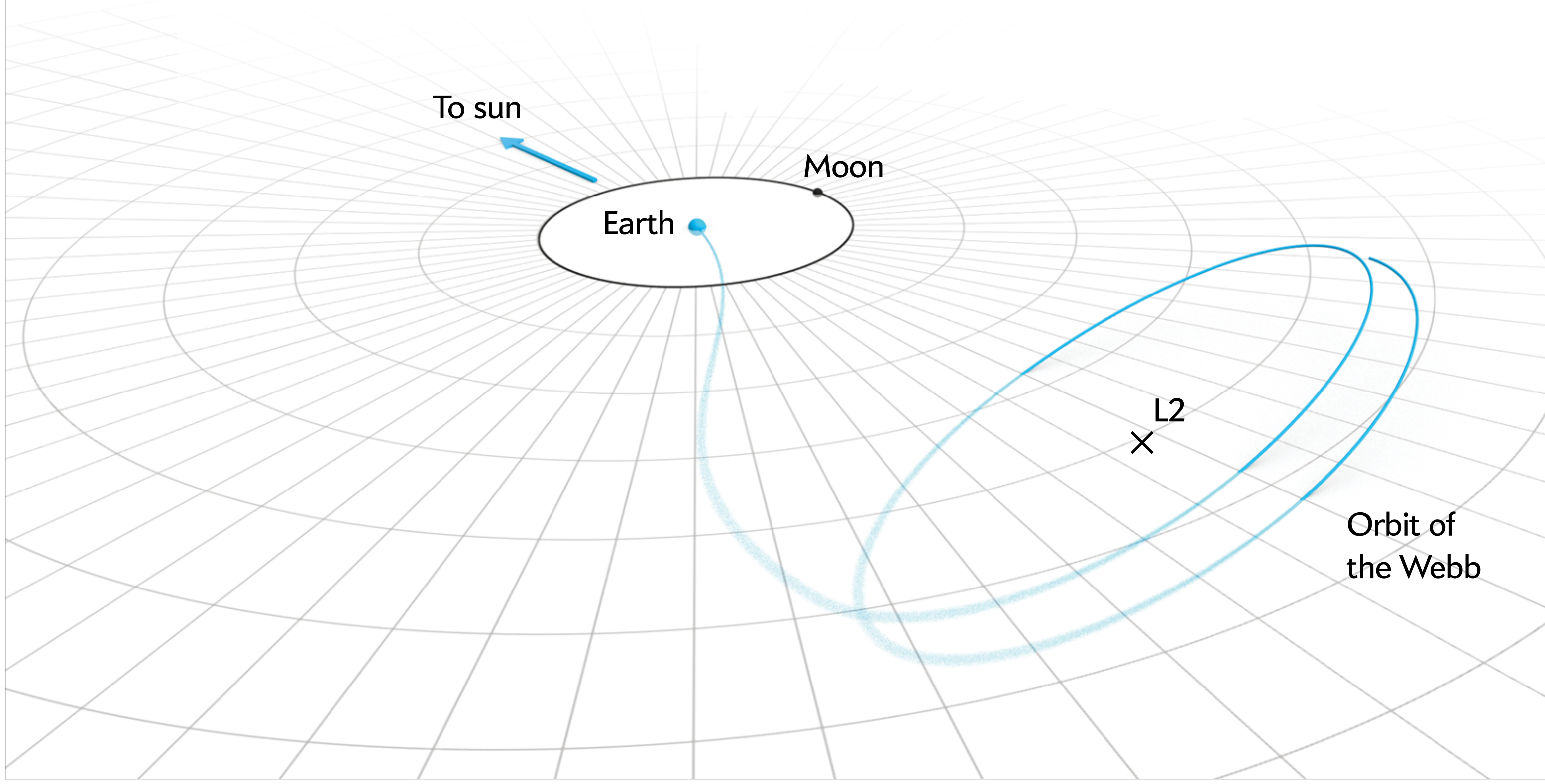
Hubble Space Telescope
Launch: April 24, 1990
Mirror size: 2.4 m

James Webb Space Telescope
Mirror size: 6.5 m



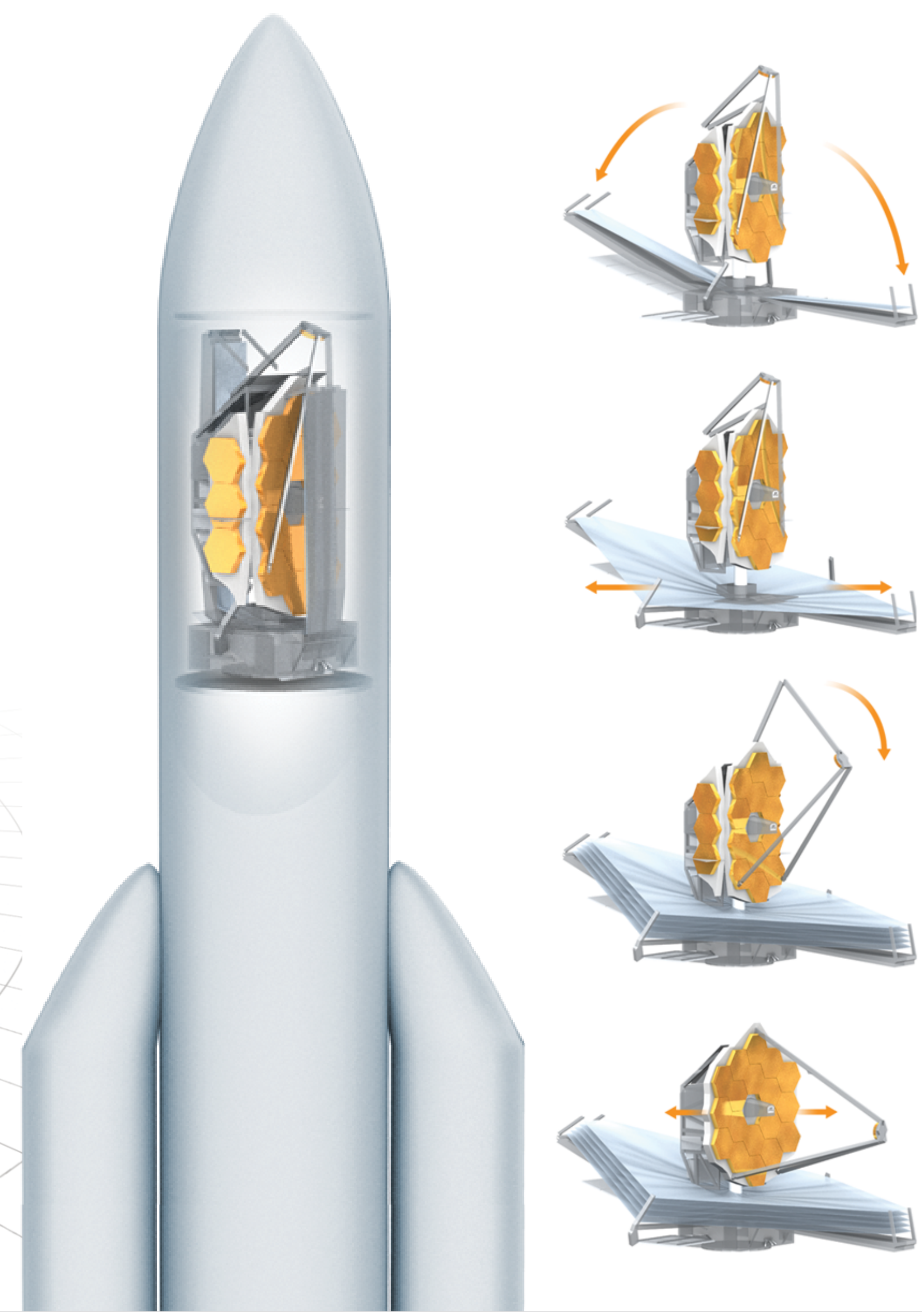
The Orbit

Whereas most satellites follow circular or elliptical orbits around our planet, the Webb telescope won't orbit Earth at all. Instead it will loop every six months around the gravitational balancing point known as L2, short for second Lagrangian point, which itself circles the sun.



The Chrysalis

The six-metric-ton telescope is too large to fit inside an Ariane 5—or inside any rocket, for that matter. Instead it will launch with six of its mirror segments folded back like the sides of a drop-leaf dining table. The secondary mirror scaffolding and the sunshield will also unfold only after the telescope reaches deep space.



Bryan Christie Design

THE BLOOM OF WEBB

Once it is about 10,400 kilometers into its trip, Webb will detach from the Ariane 5's second stage, signifying the end of the launch. Nevertheless, the most nerve-racking part of Webb's journey will have only just begun: a 1.5-million-kilometer cruise to L2, during which the folded telescope will slowly begin to unfurl.

"That's when the nail-biting starts," Hammel says. "We aren't there. We can't make adjustments, so things must work well."

Just moments after separating from its rocket, Webb's solar-power array will unfold to begin supplying electricity to the spacecraft. Although the solar-array deployment is a relatively simple procedure, its success is critical to power all following operations, Stiavelli says.

About 12 hours after launch, the craft's thrusters will fire for the first time to correct its trajectory. Course corrections must be efficient to preserve the telescope's fuel and maximize its life span, Stiavelli says. Confirmation of a successful course correction will not arrive until well after the fact, although subsequent tweaks to Webb's flight trajectory can be made if needed.

As the telescope nears its third day in space, Webb will begin to deploy one of its most intricate and prominent instruments: the sunshield. If unspooled without a hitch, a stack of five enormous kite-shaped sheets of polyimide film will block sunlight and heat from reaching the telescope's infrared sensors, which must remain at extremely low cryogenic temperatures to function properly.

The sunshield is crucial for keeping the telescope sufficiently cold so that it can sense the infrared glow of cosmic dawn, Hammel says. "The deployment has got to go well," she adds.

But to open the sunshield, around 150 release mechanisms must fire correctly over the course of three days. The complicated deployment involves around 7,000 parts, including 400 pulleys, eight motors and 140 release actuators. The sunshield's deployment is key to achieving scientists' wildest dreams for the observatory. But for aerospace engineers, the procedure's complexity and high number of single-point failures are the stuff of nightmares.

"It's a big task: getting these five extremely thin layers that are each the size of a tennis court all stretched out and separated from each other," Hammel says. And the anxiety will not fade with a nominal sunshield deployment. Six days into the flight, the telescope's secondary mirror, positioned at the end of three long arms, will lower into place. Despite its name, the secondary mirror is a critical component for Webb's success, Hammel says. If other deployments do not work out perfectly, there may be work-arounds. "But if the secondary mirror doesn't deploy successfully, we have no telescope," she says. "We got nothing."

On the seventh day Webb's 6.5-meter primary mirror, a collection of 18 beryllium-hewn, gold-plated hexagonal segments, will begin to unfurl. First, two "wings" will swing out and lock into place like pieces of a folding table. Then tiny actuators will push or pull each of the mirror segments into a micron-precise alignment, producing the primary mirror's singular focus. Deploying and aligning the primary mirror will involve 132 actuators and motors, each of which must function properly.

Finally, a month after launch, Webb should reach L2, concluding one of the most audacious spaceflights ever attempted and allowing the world's astronomers to collectively exhale.

"We've been practicing for this for years," Hammel says. "This is like an orchestra concert with hundreds of people all playing different instruments. Everybody has to have practiced their part, and all the instruments have to be ready. And then we play the music." SA

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Philip Lubin is a professor of physics at the University of California, Santa Barbara, whose primary research has been focused on studies of the early universe, as well as applications of directed energy for planetary defense and relativistic propulsion.
Alexander Cohen is a research scientist in the department of physics at U.C. Santa Barbara. Having graduated with a B.S. in physics in 2019, Cohen now researches applications of directed energy, primarily for spacecraft propulsion and planetary defense from asteroids.

PLANETARY SCIENCE

Planetary Defense Is Good–but Is Planetary Offense Better?

A new approach could mitigate the most damaging effects of an imminent asteroid or comet strike—or ensure many threatening objects never get close to striking Earth in the first place

Eric Simonsen/Getty Images

Less than eight years from now, on Friday the 13th of April 2029, a 370-meter-wide asteroid called Apophis will pass by the Earth, coming nearer to our planet than geosynchronous satellites. But despite the calendrical bad omen, this will be a lucky day: Apophis will not strike our planet—this time, anyway (its orbit ensures Apophis will visit us again in 2036, 2051, 2066, and so on). In 2029 this asteroid's passage will instead be a cosmic close shave, the equivalent of a speeding bullet brushing against the hairs on your head—in which the "bullet" carries the equivalent impact energy of all the world's nuclear arsenals combined.

Such dangerous liaisons are shockingly fre-

quent. On September 30, 2054, and September 23, 2060, an even larger asteroid packing an even more potent wallop, the half-kilometer-wide Bennu that was recently visited by NASA's OSIRIS-REx spacecraft will also swoop close to Earth.

Neither Bennu nor Apophis is large enough to be an existential threat—impact by either could destroy cities and devastate geographical regions but would not send humanity spiraling into extinction like the 10-kilometer-wide impactor that snuffed out the dinosaurs some 66 million years ago. Still, these asteroids remain especially worrisome because the further into the future we look, the harder it becomes to know with certainty whether or not any particular encounter will result in a disastrous impact event. Both objects are so-called gravitational-keyhole threats—the possibility that during a close pass they will traverse a small, specific region of near-Earth space in which our planet's gravity tweaks their trajectories just so to cause a future encounter to end in an Earth impact. In short, they each pose a chronic but hazy threat, one so insidious that it could lull us into a state of false complacency about the all too real risks.

We do not have to accept this anxiety-inducing status quo. Rather than merely biting our nails each time these and other potentially hazardous space rocks fly by, we should consider another option, a "plan B."

A LAST LINE OF DEFENSE

Our current approach to planetary defense boils down to wishful thinking that nothing bad will happen soon and that we will eventually figure out a solution. So far we have been focused on "situational awareness" to understand the threats. This is necessary but not sufficient for actually protecting Earth from asteroids. And the standard next step—deflecting potential threats so they will not hit us—has problems of its own, chiefly that successful deflection often requires intervention many years in advance. In this mode, many space rocks found hurtling toward imminent impact with Earth would already have slipped through all our defenses. There is, however, another way, one that promises to radically change our ability to protect ourselves.

A diagram of the authors' proposed "Pulverize It!" planetary defense system. Rocket-launched "interceptors" (*left*) deploy ahead of an incoming asteroid (*right*), breaking it into smaller fragments that then disintegrate and burn in Earth's upper atmosphere (*bottom*).

Alexander N. Cohen/U.C.S.B./Peter Cohen

The basic principle is simple to understand. Imagine you are Roger Rabbit playing a dangerous game of chance, choosing between two unopened doors. Behind door number one you get a 500-kilogram grand piano being dropped on your head from a height of one kilometer. Behind door number two you get 500 kilograms of foam balls dropped on you from the same height. Which do you choose? If you are Roger, you might choose door number one, but a *Scientific American* reader would choose door number two. Why? Both possess the same mass and potential energy, but basic intuition suggests that large numbers of foam balls will not cause the same damage to you as one piano. Fragmenting the mass into smaller portions ensures that each will carry far less energy and will also allow the atmosphere to more effectively slow each fragment's fall.

This is a rather precise analogy to our pro-

posed planetary defense method, which we affectionately call "PI" (pronounced like π), which is short for "Pulverize It!"

Our idea (which is detailed in several technical papers submitted for peer-reviewed publication and available on our Web site and arXiv) is to effectively pulverize any threatening asteroid into a large number of smaller fragments circa 10 meters or less in diameter. This is possible because asteroids have low surface gravity and most are easy to break up and disperse. For all but the largest impactors (greater than a kilometer wide), such fragmentation could be achieved using barrages of nonnuclear interceptors launched from Earth or its vicinity using existing launch systems and associated technologies. Our same system using small nuclear penetrators is also an option for large threats.

Once fragmented, the incoming impactor's energy would be efficiently converted into heat, sound and light by Earth's atmosphere, which would act much like a bulletproof vest absorbing a blast of buckshot. Our analysis shows this approach works incredibly well at mitigating imminent threats: An impactor the size of the 20-meter-wide space rock that broke up over Chelyabinsk, Russia, in February 2013 could be intercepted a mere 100 seconds prior to impact, whereas one the size of the Tunguska impactor (50 meters in diameter) would require interception some five hours prior to impact. Something the size of Apophis could be dealt with 10 days prior to striking Earth, and something as large as Bennu would need to be fragmented 20 days in advance. These are extraordinarily short intercept times compared with deflection approaches. Even shorter times would be enabled with more energetic interceptors if required.

Of course, a knowledgeable reader may realize we have not told the entire story. Both the previously mentioned Chelyabinsk and Tunguska impacts were airburst events after all, and in both cases, surrounding natural and artificial structures sustained significant damage. This damage chiefly came from the sonic-boom-like acoustic blast waves emitted by the bodies as they broke apart in the atmosphere.

Our PI approach would not eliminate airbursts, but by shattering incoming bodies before they enter the atmosphere, the resulting small fragments would be spread out over larger geographical areas and would each produce much smaller blast waves that would critically arrive at different times. Just as you'd expect to have bruising and soreness from a bulletproof vest absorbing a buckshot blast, so, too, would one expect some damage to still occur on the ground from the acoustic shock wave and associated flash of light and heat as a threatening asteroid's tumbling fragments burned up in the skies overhead.

But this damage would be slight in comparison to the alternative; for a Chelyabinsk-like impactor, a person on the ground would experience a series of loud "booms" and see a series of optical flashes—a "sound and light show" with some broken windows rather than a cataclysm that lays waste to a city, region or country.

DEMONSTRATIONS AND DETECTIONS

Despite our system's ability to leverage existing technologies and launch vehicles, its creation would nonetheless require major investments. In short, this would be expensive. But even so, the cost-benefit ratio is remarkably favorable given the almost incalculable damage that would be associated with failing to prevent an asteroid strike.

Furthermore, its creation would allow us more flexibility in dealing with known impact threats, now and on into the distant future. Much as mass vaccination programs are used to proactively prevent against pandemics, PI offers a way to proactively address many asteroids that, while potentially hazardous in their Earth-crossing orbits, pose no immediate threat. While likely a controversial approach, it is little different from other proactive threat management we practice in life. We could mitigate threats such as Apophis and Bennu on any given close pass before they spark full-blown emergencies. It is within our power to do so. Whether we do so or not is not just a technical issue but one of policy and cooperation and common agreement. This is an area where international cooperation could benefit the entire planet; much like the current emphasis on collectively solving Earth's climate and pandemic crisis, we can come together to solve the "impact" crisis, too.

Mitigating a Chelyabinsk-size threat could be done using a relatively small rocket that is not much larger than those developed to intercept intercontinental ballistic missiles. Mitigating Apophis or Bennu can be done with a single

larger launcher such as NASA's forthcoming Space Launch System, SpaceX's Starship rocket, or even smaller vehicles carrying high-speed upper stages for rapid transit beyond the vicinity of Earth's moon. Multiple interceptors would be desirable to boost chances of success. A future planetary defense system might deploy interceptors in orbit or on or around the moon for an "always at the ready" rapid response approach. In this sense, a planetary defense system could be analogous to existing national missile defense systems.

PI has a logical test path, from ground demonstrations using asteroid "mock-ups," to in-space testing on "synthetic targets," all the way to disruption attempts for small, minimally threatening asteroids and other validating exercises before any actually threatening target is engaged and mitigated.

Yet we cannot mitigate that which we cannot see. NASA and other space agencies are doing an excellent job of finding and tracking those asteroids that are significant threats, but currently these efforts are generally limited to objects typically larger than Apophis. There are many smaller as yet undetected threats that exist, as the Chelyabinsk airburst showed so clearly in 2013. Without a suitable, separately developed "early-warning system," PI and any other planetary defense method would offer suboptimal protection. PI is just one piece of this urgent puzzle: to properly protect Earth, we must fully open more eyes on the skies.

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CONSCIOUSNESS

Death, Physics and Wishful Thinking

Fear of mortality might underlie physicists' fondness for the anthropic principle, multiverses, superdeterminism and other shaky ideas

Klaus Vedfelt/Getty Images

Our quirky minds thwart psychologists' efforts to find durable theories. But terror-management theory has held up quite well since three psychologists proposed it more than 30 years ago. It holds that fear of death underpins many of our actions and convictions. We cling to our beliefs more tightly when reminded of our mortality, especially if those beliefs connect us to something transcending our puny mortal selves.

Terror-management theory can account for puzzling political trends, such as our attraction to outlandish conspiracies and authoritarian leaders. In 2020 I invoked the theory to explain why Donald Trump's popularity surged at the beginning of the COVID-19 pandemic. Recently I have begun to wonder whether terror-management theory can explain trends in physics, too.

Physicists pride themselves on their rationality, yet they are as prone to existential dread as the rest of us, if not more so. Their investigations force them to confront infinity and eternity in their day jobs, not just in the dead of night. Moreover, physicists' equations describe particles pushed and pulled by impersonal forces. There is no place for love, friendship, beauty, justice—the things that make life worth living. From this chilly perspective, the entirety of human existence, let alone an individual life, can seem terrifyingly ephemeral and pointless.

Steven Weinberg, arguably the greatest physicist of the past half-century, urged us to accept the soul-crushing implications of physics, and he rejected attempts to turn it into a substitute for religion. In *Dreams of a Final Theory*, Weinberg said science cannot replace "the consolations that have been offered by religion in facing death." Weinberg, who died in July 2021,

was unusually resistant to wishful thinking (except for his thinking about a final theory). Other physicists, I suspect, cling to certain hypotheses precisely because they make mortality more bearable. Below are examples.

WE WERE MEANT TO BE HERE

There is a whole class of conjectures that, like religion, give us a privileged position in the cosmic scheme of things. Call them we-were-meant-to-be-here theories. They imply that we are not an accidental, incidental part of nature; our existence is somehow necessary. Without us, the universe might not exist. One example is the anthropic principle, which dates back to the 1960s. The anthropic principle suggests that the laws of nature must take the form that we observe because otherwise we would not be here to observe them.

The anthropic principle is a tautology masquerading as a truth, but it has proved remarkably resilient. Stephen Hawking took it seriously, as did Weinberg. A major reason for the endurance of the anthropic principle is the proliferation of multiverse theories, which hold that our universe is just one of many. If you buy multiverses (to which I will return later), the anthropic principle can help explain why we find ourselves in this particular universe with these particular laws.

Quantum mechanics has inspired lots of we-were-meant-to-be-here proposals because it suggests that what we observe depends on how we observe it. Look at an electron this way, it behaves like a particle; that way, it resembles a wave. Physicists, notably Eugene Wigner and John Wheeler, have speculated that consciousness, far from being a mere epiphenomenon of matter, is an essential component of reality. Your individual consciousness might not endure, but consciousness of some kind will last for as long as the universe does. I critique these we-were-meant-to-be-here propositions here and here.

NOTHING EVER ENDS

A more subtle source of consolation is what Richard Feynman, in *The Character of Physical Law*, calls “the great conservation principles.” According to these laws, certain features of nature remain constant, no matter how much nature changes. The best-known conservation law involves energy. Energy can take many forms—kinetic, potential, electrical, thermal, gravitational, nuclear—and it can change from one form into another. Matter can become energy, and vice versa, as Einstein revealed with his famous equation $E = mc^2$. But if you add up all the kinds of energy at any given instant, that sum remains constant.

Other conservation laws apply to angular momentum and charge. In what way are these laws consoling? Because to be human is to know loss. When we look at the world—and at our own faces in the mirror—we see the terrible transience of things. What we love will vanish sooner or later. It is reassuring to know that, on some level, things stay the same. According to conservation laws, there are no endings or beginnings, only transformations.

The most consoling conservation law involves information. Physicist Leonard Susskind says conservation of information “underpins everything, including classical physics, thermodynamics, quantum mechanics, energy conservation, that physicists have believed for hundreds of years.” According to the law, everything that happens leaves its imprint, permanently, on the universe. Eons after you die, after the earth and the sun have vanished, every minute detail of your life will endure in some form—supposedly.

Back to multiverse theories, which stipulate that our universe is just one among multitudes. Physicists have proposed different multiverse theories inspired by quantum mechanics, string theory and inflation, a speculative theory of cosmic creation. What the theories all have in common is a lack of evidence—or even the hope of evidence. So what explains their popularity?

Here is my guess: physicists are freaked out by the mortality of our little universe. What was born must die, and according to the big bang theory, our cosmos was born 14 billion years ago, and it will die at some unspecified time in the far future. The multiverse, like God, is eternal. It had no beginning; it will have no end. If you find that proposition reassuring, perhaps you shouldn’t read this critique of multiverse theories.

THE UPSIDE OF DETERMINISM

Determinism, physics-style, assumes that reality is strictly physical. Everything that happens, including our choices, results from physical forces, like gravity pushing and pulling physical objects.

Moreover, every present moment is associated with a single unique past and a single unique future. I do not like determinism, because it subverts free will and makes us more likely to accept that the way things are is the way they must be.

But I can see the upside of determinism. The world often seems disturbingly out of control. We have the sense that at any moment bad things might happen, on scales small and large. A truck might strike you as you cross the street, absent-mindedly brooding over quantum mechanics. A nearby supernova might bathe the earth in lethal radiation. Millions of my fellow citizens might become enthralled by a thuggish buffoon. A mutant virus might suddenly emerge from who knows where and kill millions of people.

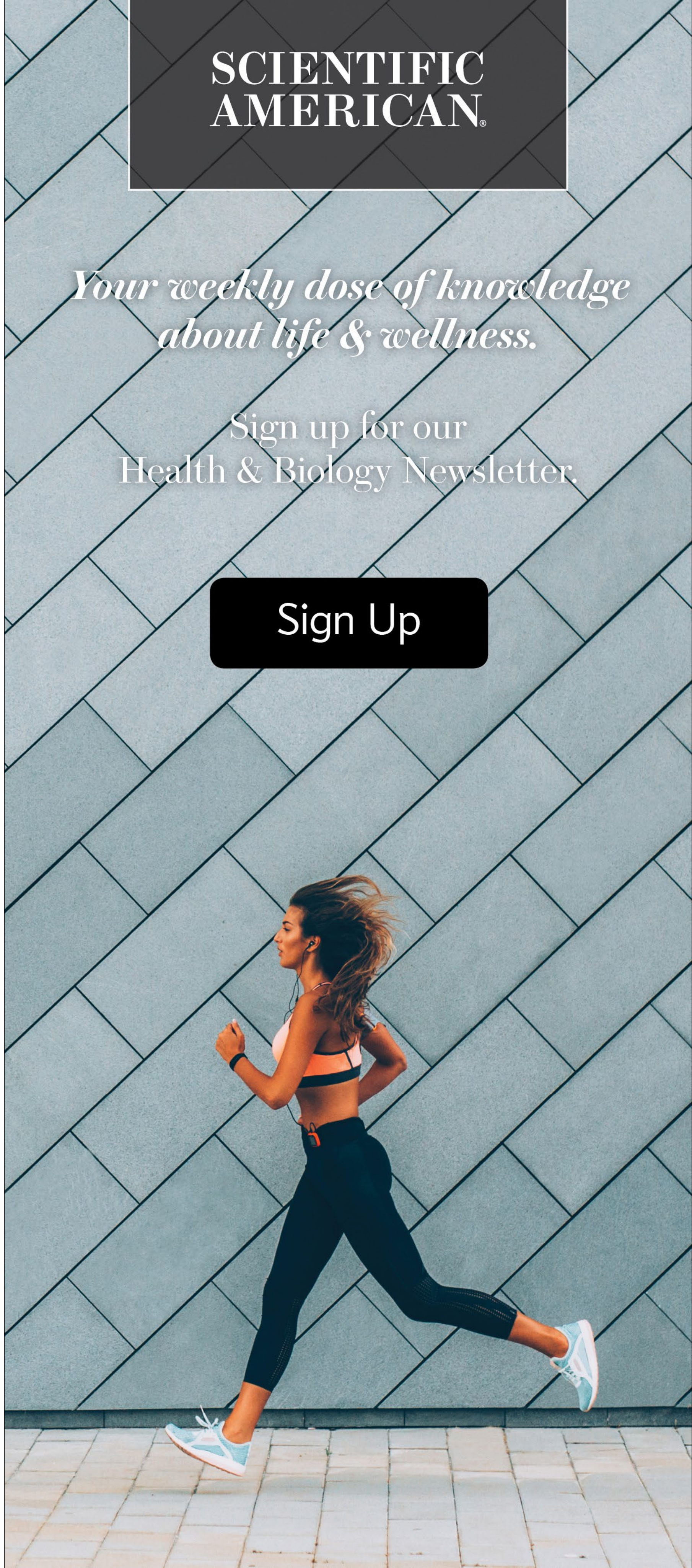
We desperately want to believe that beneath the apparent randomness, someone or something is in control. God, for many people, is the tough but fair chief executive running this seemingly chaotic cosmic corporation. It is hard for us to see Her/His/Their plan, but She/He/They surely know what She/He/They are doing.

If you find the God hypothesis implausible, then perhaps an extreme form of determinism, called superdeterminism, might serve as a substitute. Superdeterminism attempts to eliminate several puzzling features of quantum mechanics, including the apparent randomness of quantum events and intrusive role of measurement. Two physicists I admire, Sabine Hossenfelder and Gerard 't Hooft, have promoted the theory.

According to superdeterminism, the universe is not careening wildly into an unknowable future. It is gliding serenely, undeviatingly, along a rigid track laid down at the beginning of time. As a free-will fanatic I do not find this perspective comforting, but I understand why others do. If determinism is true, there is nothing you can do to change things, so sit back and enjoy the ride. Everything is as it should be—or must be.

The one physics principle that is hard to spin positively is the second law of thermodynamics. It decrees that all the creative energy in the universe will eventually dissipate, becoming useless heat. The marvelous, intricate structures that we see around us—stars, planets, cathedrals, oaks, dragonflies, human beings—will vanish. The universe will descend into heat death, a state in which nothing ever happens. Clever physicists have imagined ways in which we can escape this dismal fate, but their proposals do not seem much more plausible than the heaven hypothesis.

I don't find any physics hypotheses very consoling. I wish I did. I have been brooding over death a lot lately because of my advanced age and the precarious state of the world. I have my consolations. I am a writer and father, so I fantasize about people reading my books after I'm gone, and I envision my son and daughter living good, fulfilling lives and possibly having children of their own. These wishful visions require civilization to continue, so I persuade myself that civilization, in spite of its manifest flaws, is pretty good and getting better. That's how I manage my terror.



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COSMOLOGY

Was Our Universe Created in a Laboratory?

Developing quantum gravity technologies may elevate us to a "class A" civilization, capable of creating a baby universe

The biggest mystery concerning the history of our universe is what happened before the big bang. Where did our universe come from? Nearly a century ago Albert Einstein searched for steady-state alternatives to the big bang model because a beginning in time was not philosophically satisfying in his mind.

Now there are a variety of conjectures in the scientific literature for our cosmic origins, including the ideas that our universe emerged from a vacuum fluctuation, or that it is cyclic with repeated periods of contraction and expansion, or that it was selected by the anthropic principle out of the string theory landscape of the multiverse—where, as the M.I.T. cosmologist Alan Guth says "everything that can happen will happen … an infinite number of times"—or that it emerged out of the collapse of matter in the interior of a black hole.

NASA/ESA/HEIC/Hubble Heritage Team/STScI/AURA

A less explored possibility is that our universe was created in the laboratory of an advanced technological civilization. Because our universe has a flat geometry with a zero net energy, an advanced civilization could have developed a technology that created a baby universe out of nothing through quantum tunneling.

This possible origin story unifies the religious notion of a creator with the secular notion of quantum gravity. We do not possess a predictive theory that combines the two pillars of modern physics: quantum mechanics and gravity. But a more advanced civilization might have accomplished this feat and mastered the technology of creating baby universes. If that happened, then not only could it account for the origin of our universe, but it also would suggest that a universe like our own—which in this picture hosts an advanced technological civilization that gives birth to a new flat universe—is like a biological system that maintains the longevity of its genetic material through multiple generations.

If so, our universe was not selected for us to exist in it—as suggested by conventional anthropic reasoning—but rather it was selected such that it would give rise to civilizations that are much more advanced than we are. Those “smarter kids on our cosmic block”—which are capable of developing the technology needed to produce baby universes—are the drivers of the cosmic Darwinian selection process, whereas we cannot enable, as of yet, the rebirth of the cosmic conditions that led to our existence. One way to put it is that our civilization is still cosmologically sterile because we cannot reproduce the world that made us.

As of now, we are a low-level technological civilization, graded class C on the cosmic scale because we are unable to re-create even the habitable conditions on our planet for when the sun will die.

With this perspective, the technological level of civilizations should not be gauged by how much power they tap, as suggested by the scale envisioned in 1964 by Nikolai Kardashev. Instead it should be measured by the ability of a civilization to reproduce the astrophysical conditions that led to its existence.

As of now, we are a low-level technological civilization, graded class C on the cosmic scale because we are unable to re-create even the habitable conditions on our planet for when the sun will die. Even worse, we may be labeled class D because we are carelessly destroying the natural habitat on Earth through climate change, driven by our technologies. A class B civilization could adjust the conditions in its immediate environment to be independent of its host star. A civilization ranked class A could re-create the cosmic conditions that gave rise to its existence, namely, produce a baby universe in a laboratory.

Achieving the distinction of class A civilization is nontrivial by the measures of physics as we know it. The related challenges, such as producing a large-enough density of dark energy within a small region, already have been discussed in the scientific literature.

Because a self-replicating universe only needs to possess a single class A civilization, and having many more is much less likely, the most common universe would be the one that just barely makes class A civilizations. Anything better than this minimum requirement is much less likely to occur because it requires additional rare circumstances and does not provide a greater evolutionary benefit for the Darwinian selection process of baby universes.

The possibility that our civilization is not a particularly smart one should not take us by surprise. When I tell students at Harvard University that half of them are below the median of their class, they get upset. The stubborn reality might well be that we are statistically at the center of the bell-shaped probability distribution of our class of intelligent life-forms in the cosmos, even when taking into account our celebrated discovery of the Higgs boson by CERN's Large Hadron Collider.

We must allow ourselves to look humbly through new telescopes, as envisioned by the recently announced Galileo Project and search for smarter kids on our cosmic block. Otherwise, our ego trip may not end well, similarly to the experience of the dinosaurs, which dominated Earth until an object from space tarnished their illusion.

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